

# P&S Modern SSDs

## Flash Memory and Solid-State Drives

Prof. Onur Mutlu

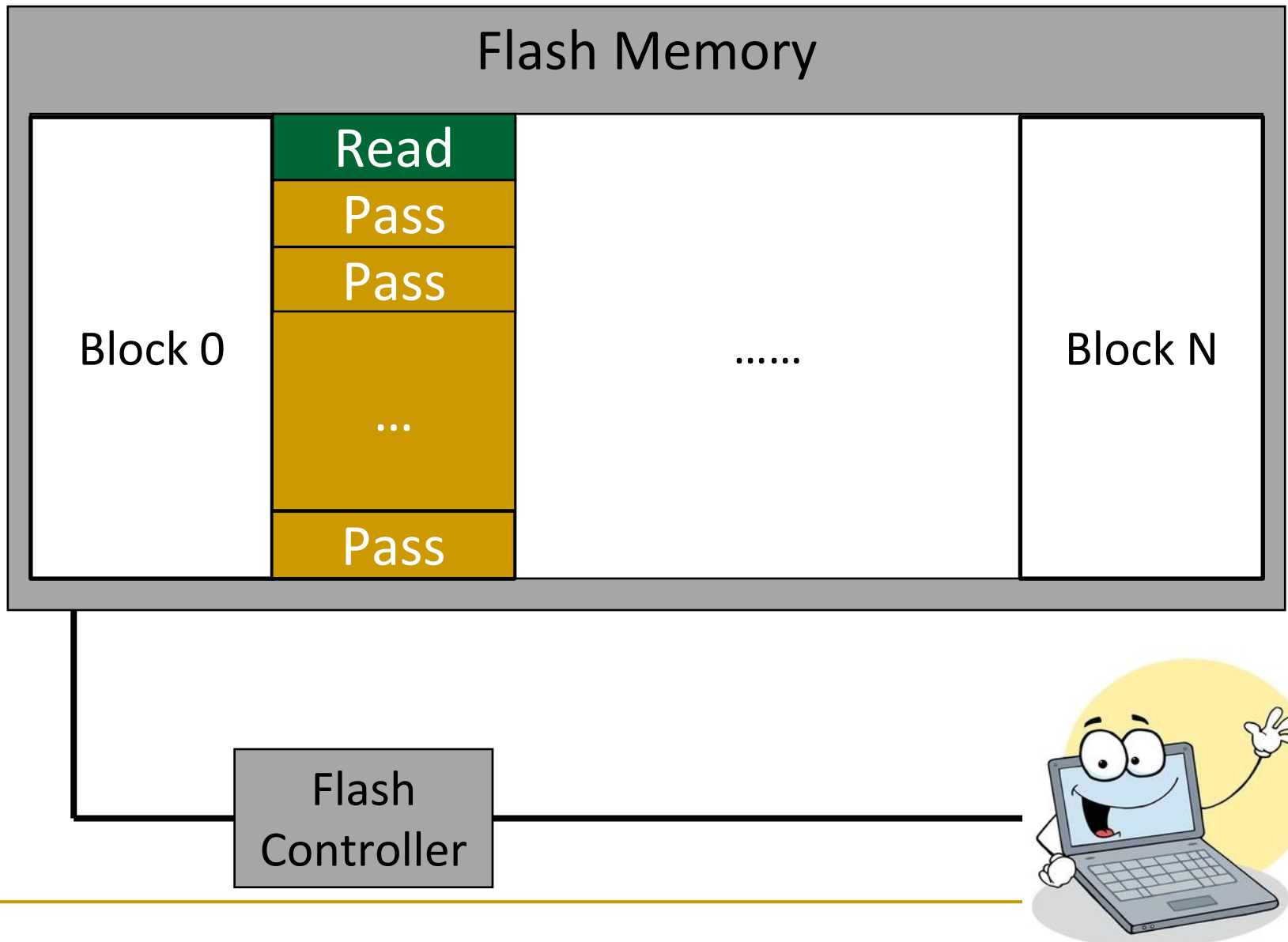
ETH Zürich

Fall 2022

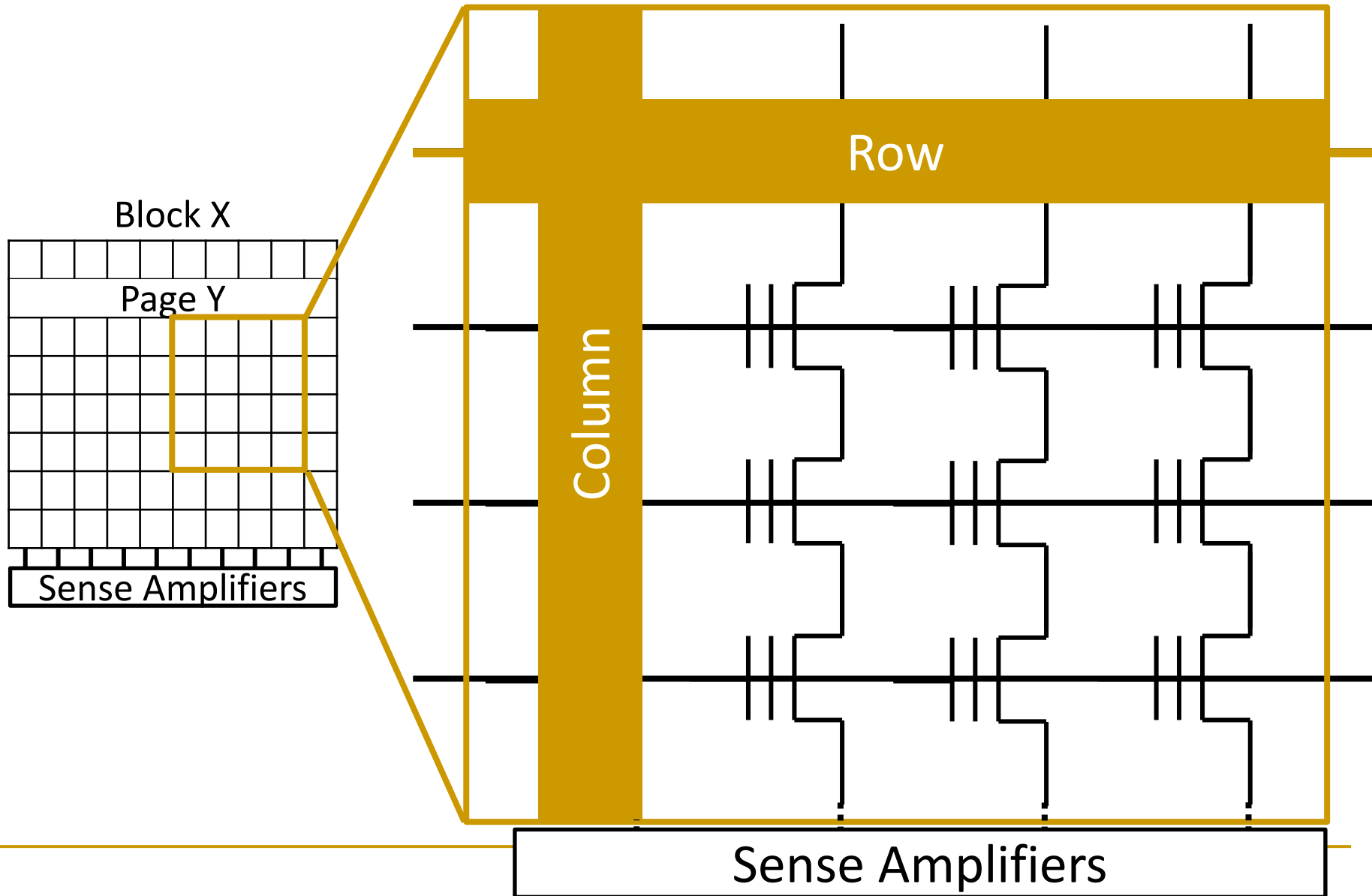
25 January 2023

# Short Background on NAND Flash Memory Operation

# NAND Flash Memory Background

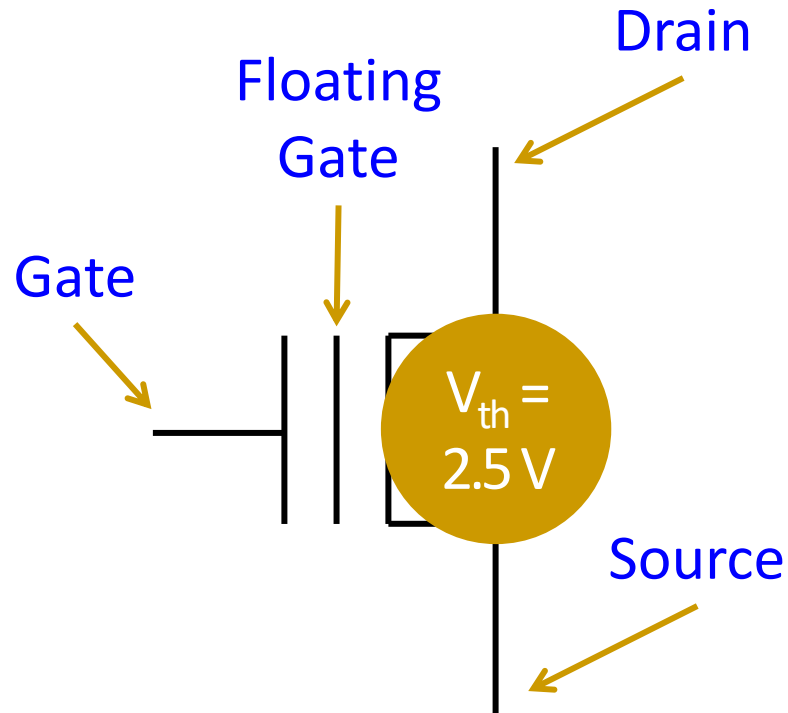


# Flash Cell Array



# Flash Cell

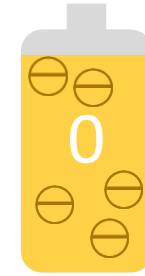
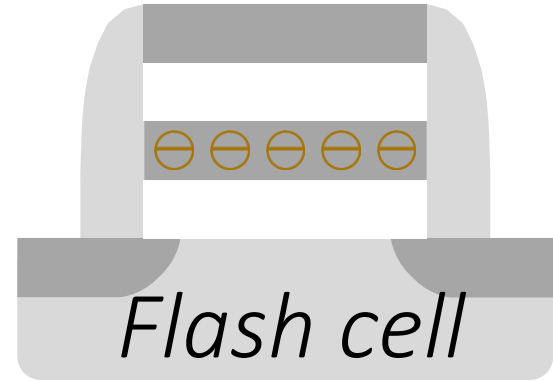
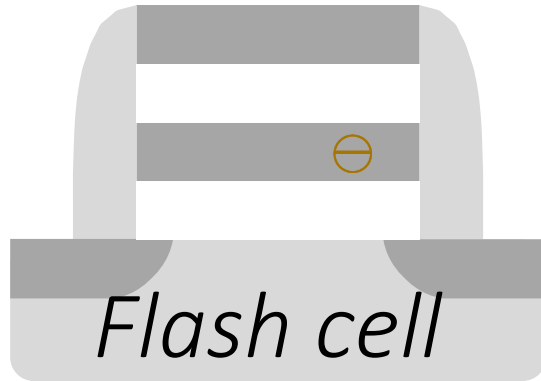
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Floating Gate Transistor  
(Flash Cell)

# Threshold Voltage ( $V_{th}$ )

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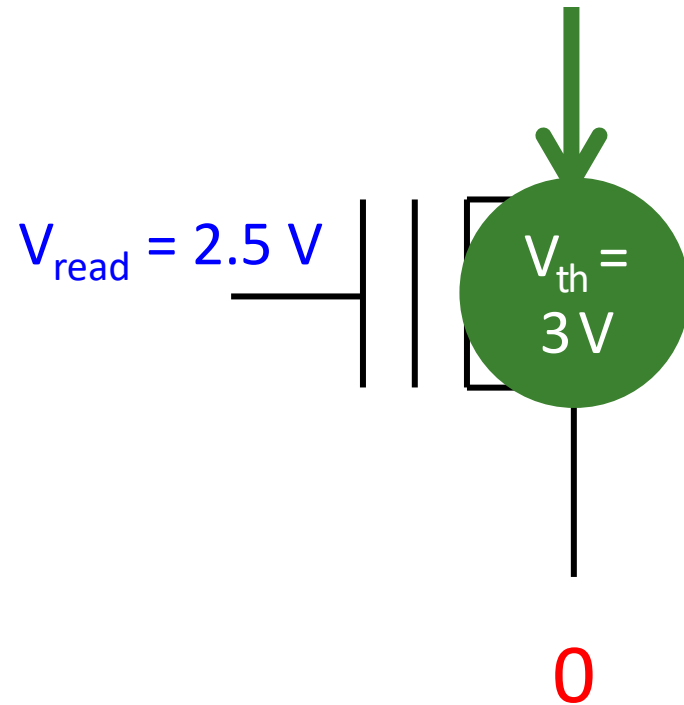
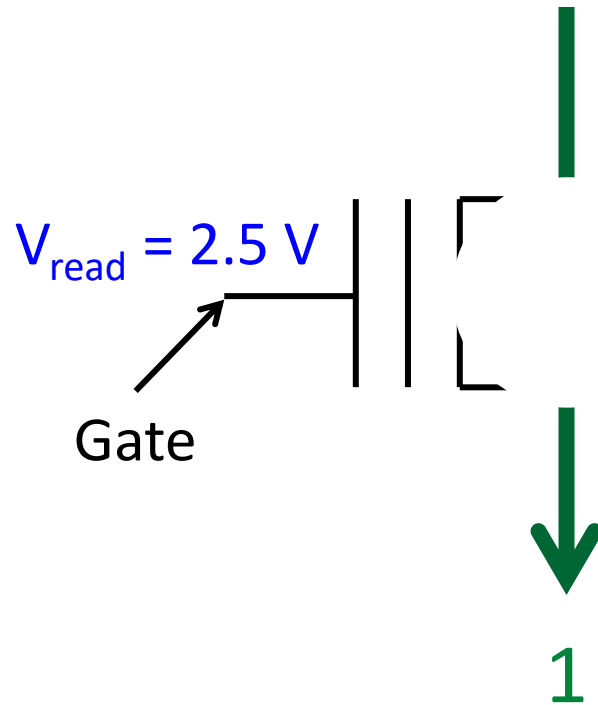


Normalized  $V_{th}$

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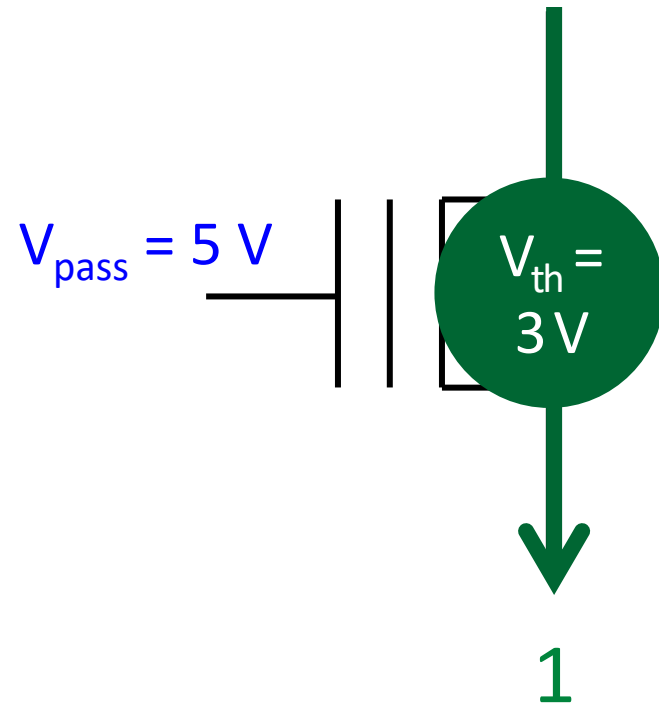
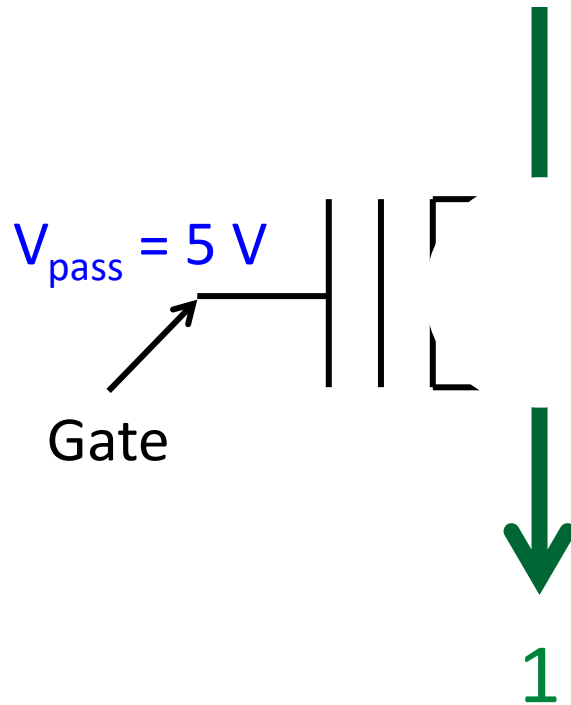
# Flash Read

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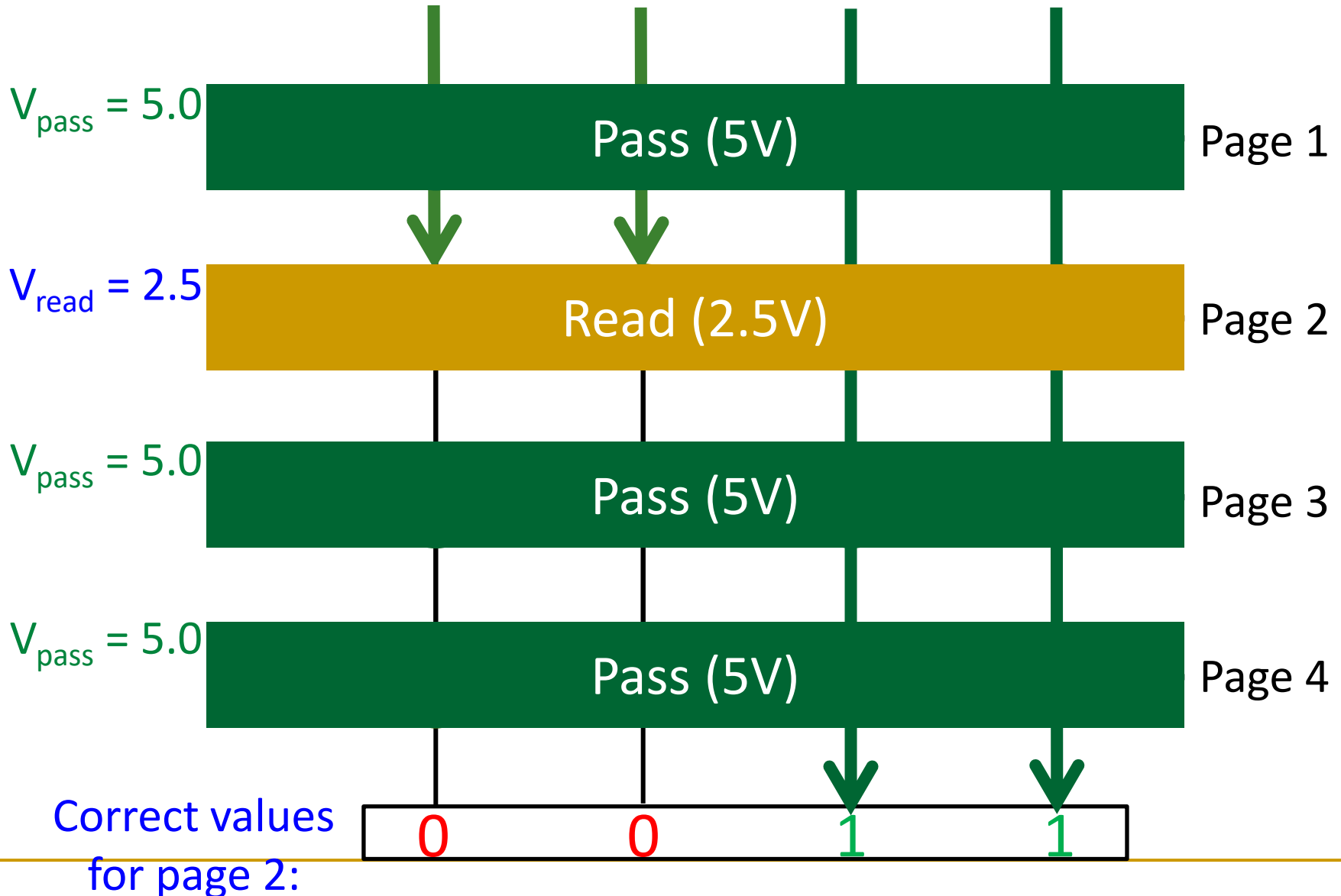
# Flash Pass-Through

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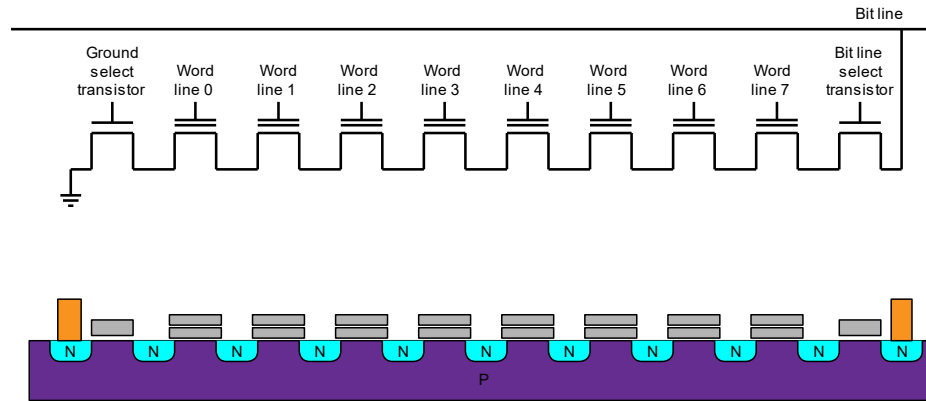


# Read from Flash Cell Array

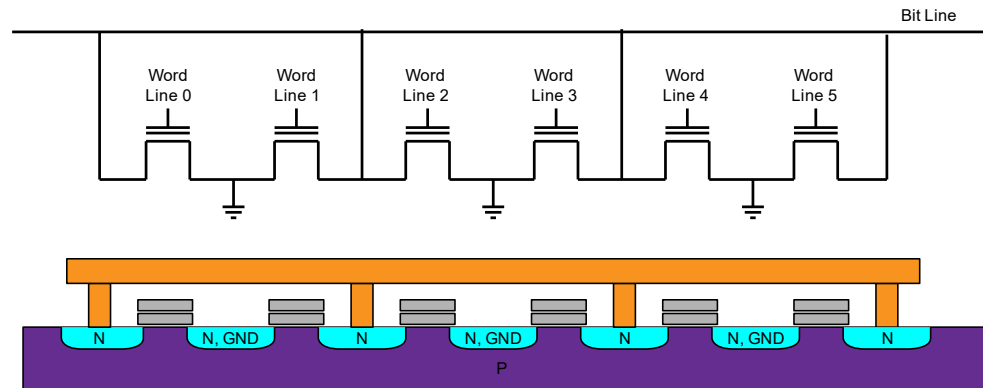


# Aside: NAND vs. NOR Flash Memory

**NAND**

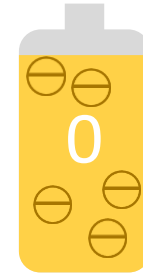
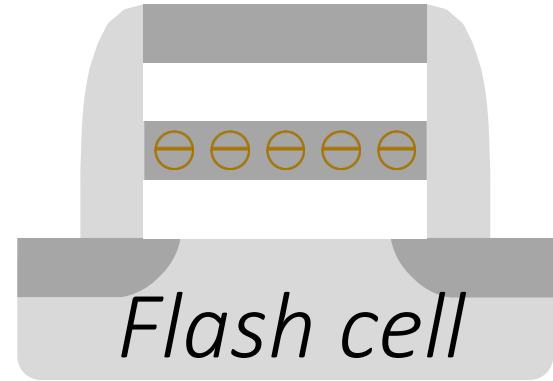
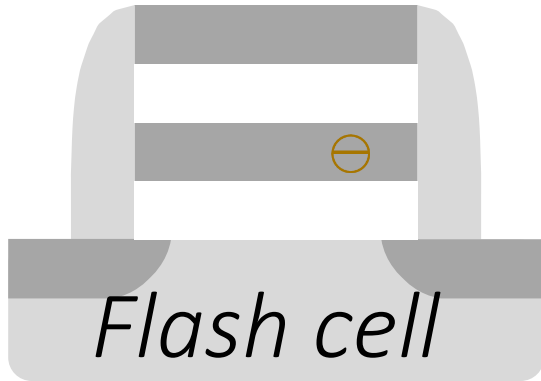


**NOR**



# Threshold Voltage ( $V_{th}$ )

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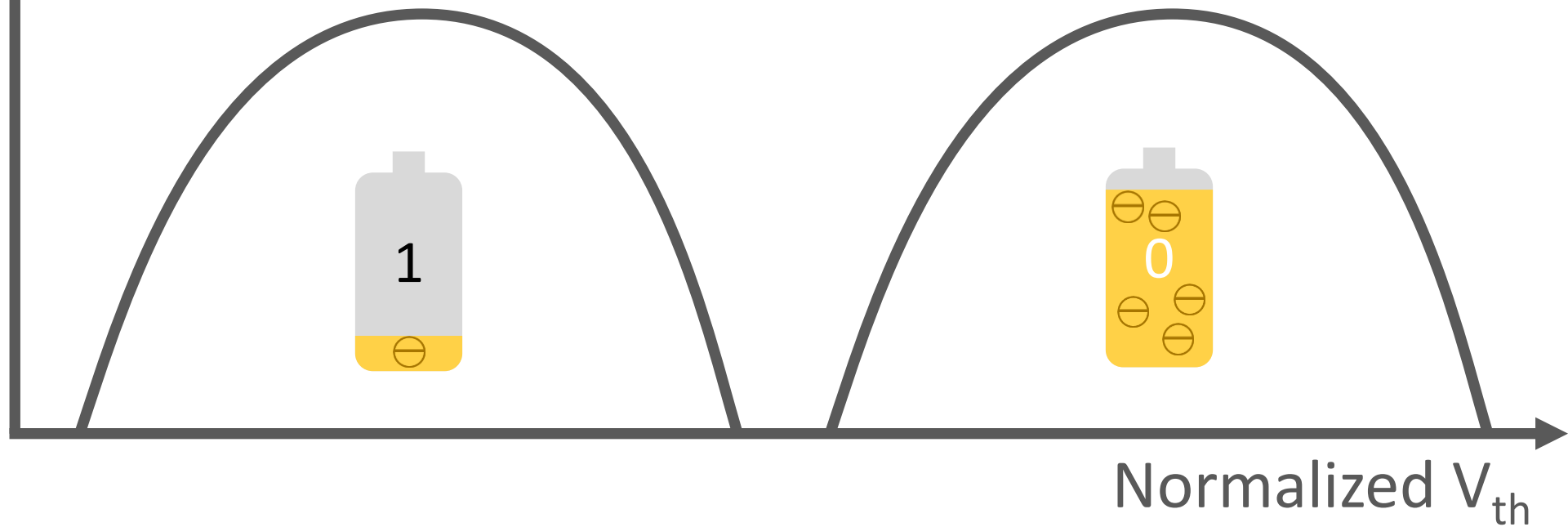
Normalized  $V_{th}$



# Threshold Voltage ( $V_{th}$ ) Distribution

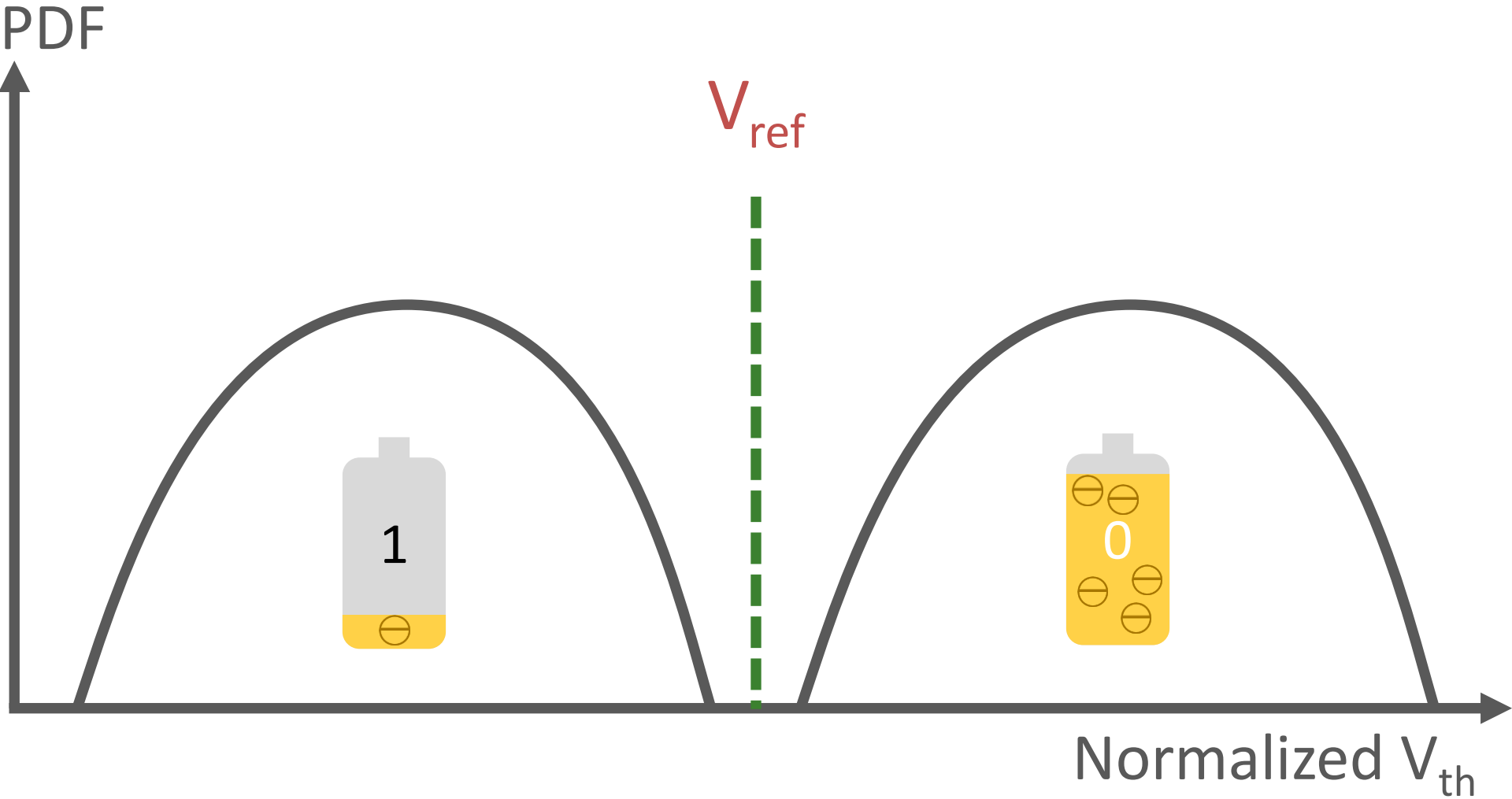
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Probability Density  
Function (PDF)

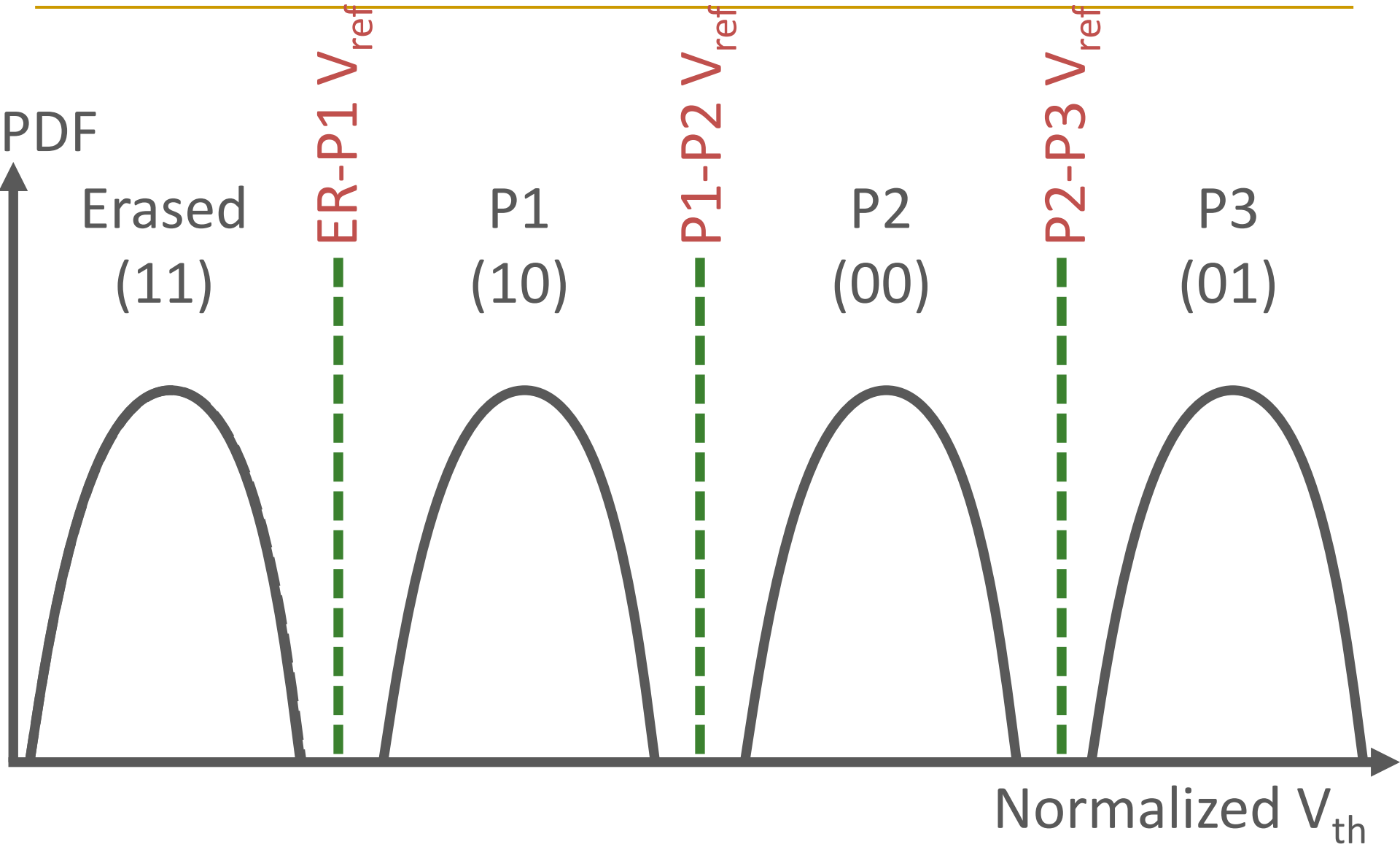


# Read Reference Voltage ( $V_{\text{ref}}$ )

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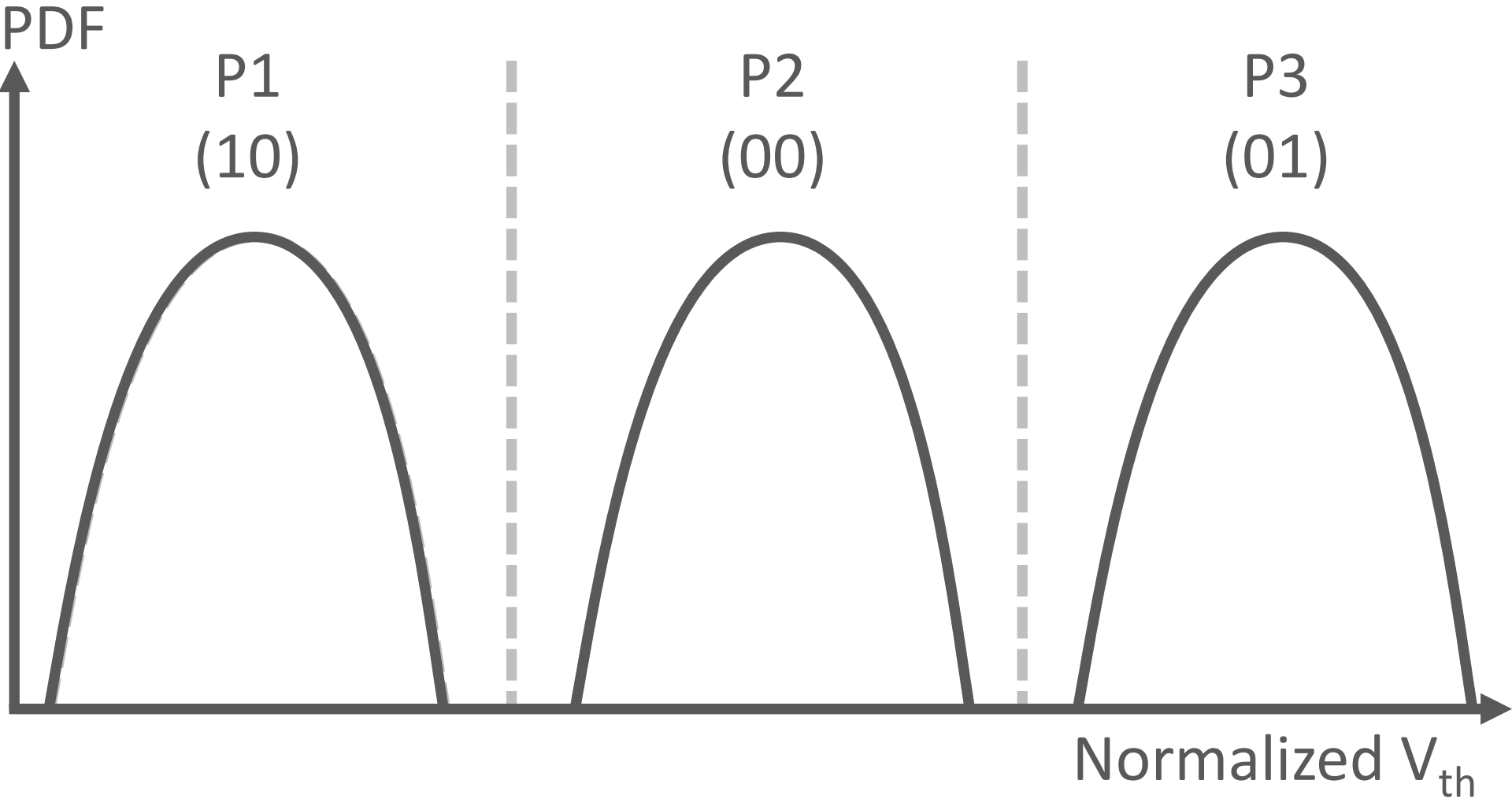


# Multi-Level Cell (MLC)



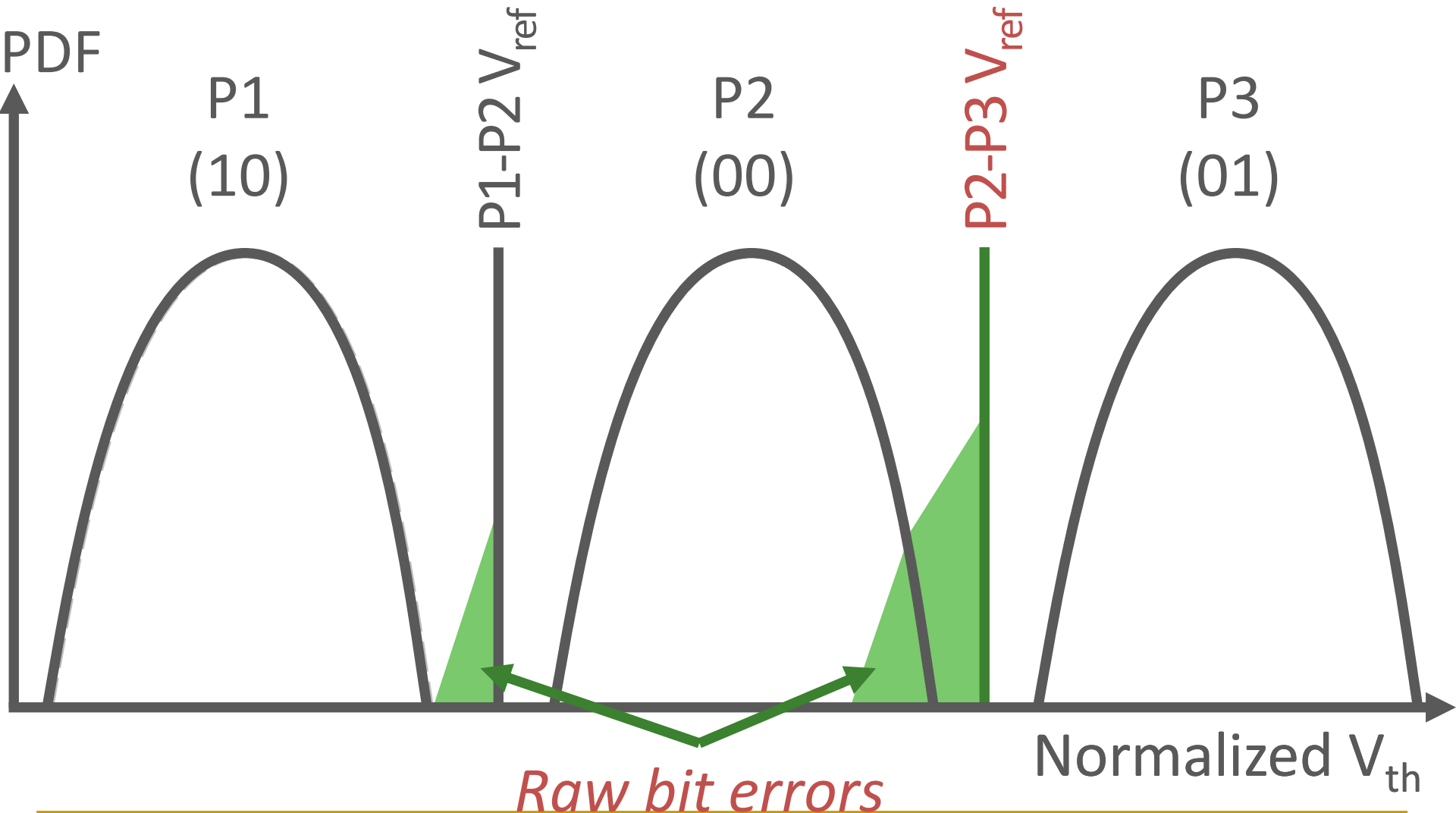
# Threshold Voltage Reduces Over Time

After some retention loss:



# Fixed Read Reference Voltage Becomes

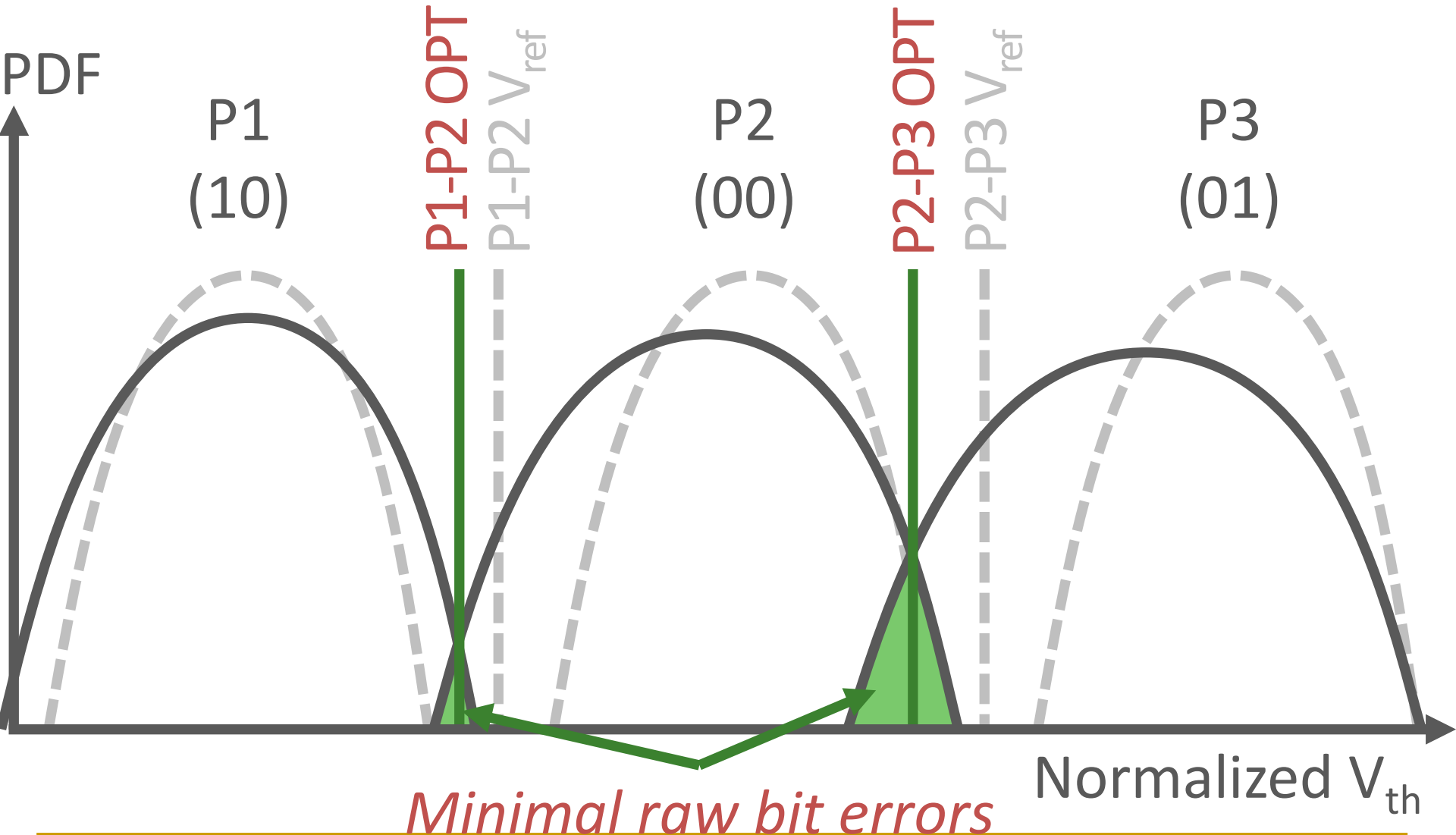
After some retention loss:





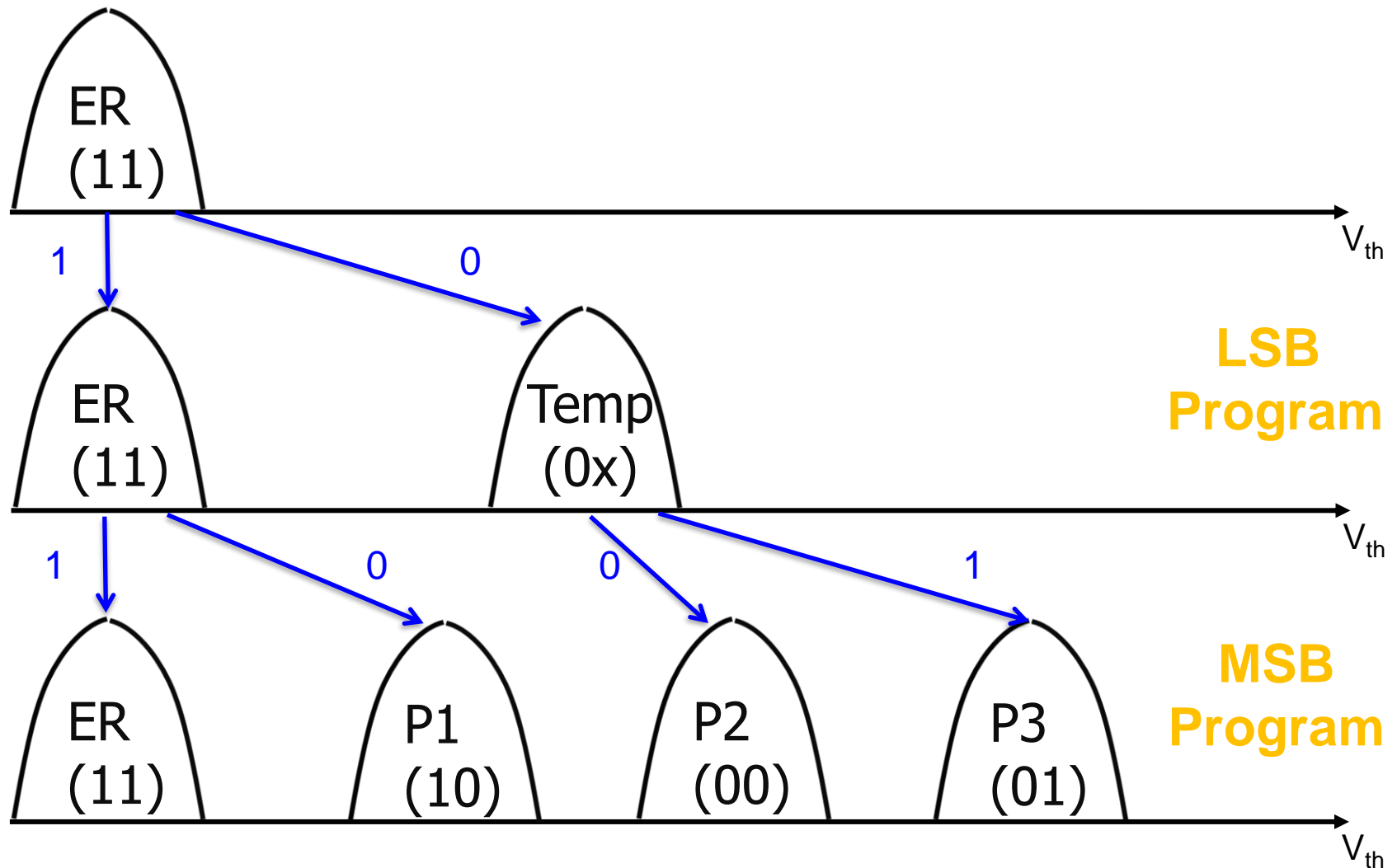
# Optimal Read Reference Voltage (OPT)

After some retention loss:

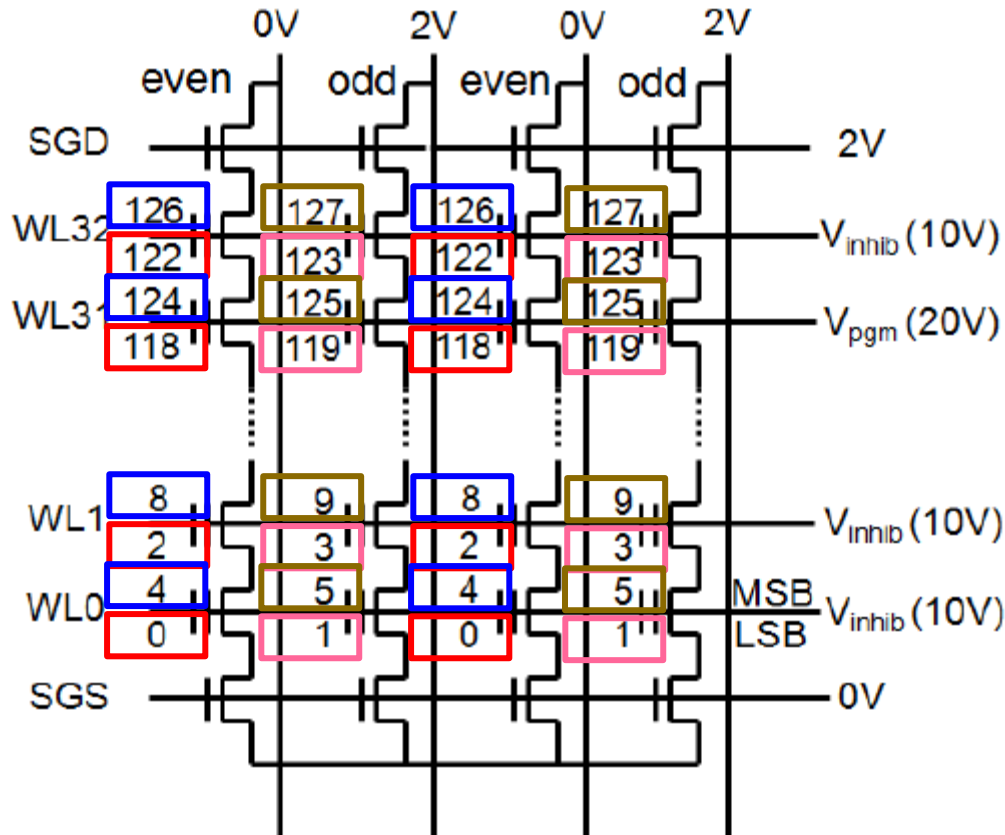


# How Current Flash Cells are Programmed

- Programming 2-bit MLC NAND flash memory in two steps



# MLC Architecture



LSB-Even Page Sets

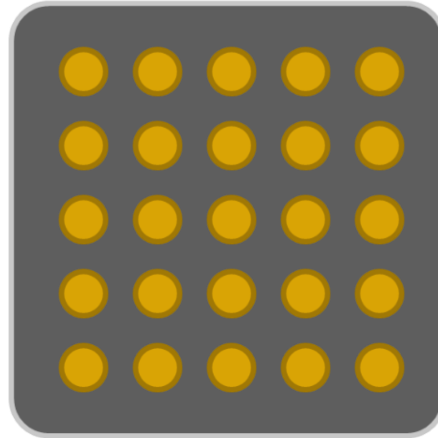
LSB-Odd Page Sets

MSB-Even Page Sets

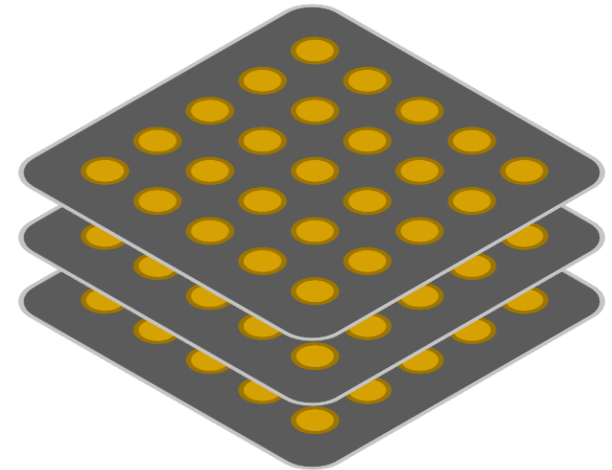
MSB-Odd Page Sets

# Planar vs. 3D NAND Flash Memory

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**Planar NAND  
Flash Memory**



**3D NAND  
Flash Memory**

## **Scaling**

Reduce flash cell size,  
Reduce distance b/w cells

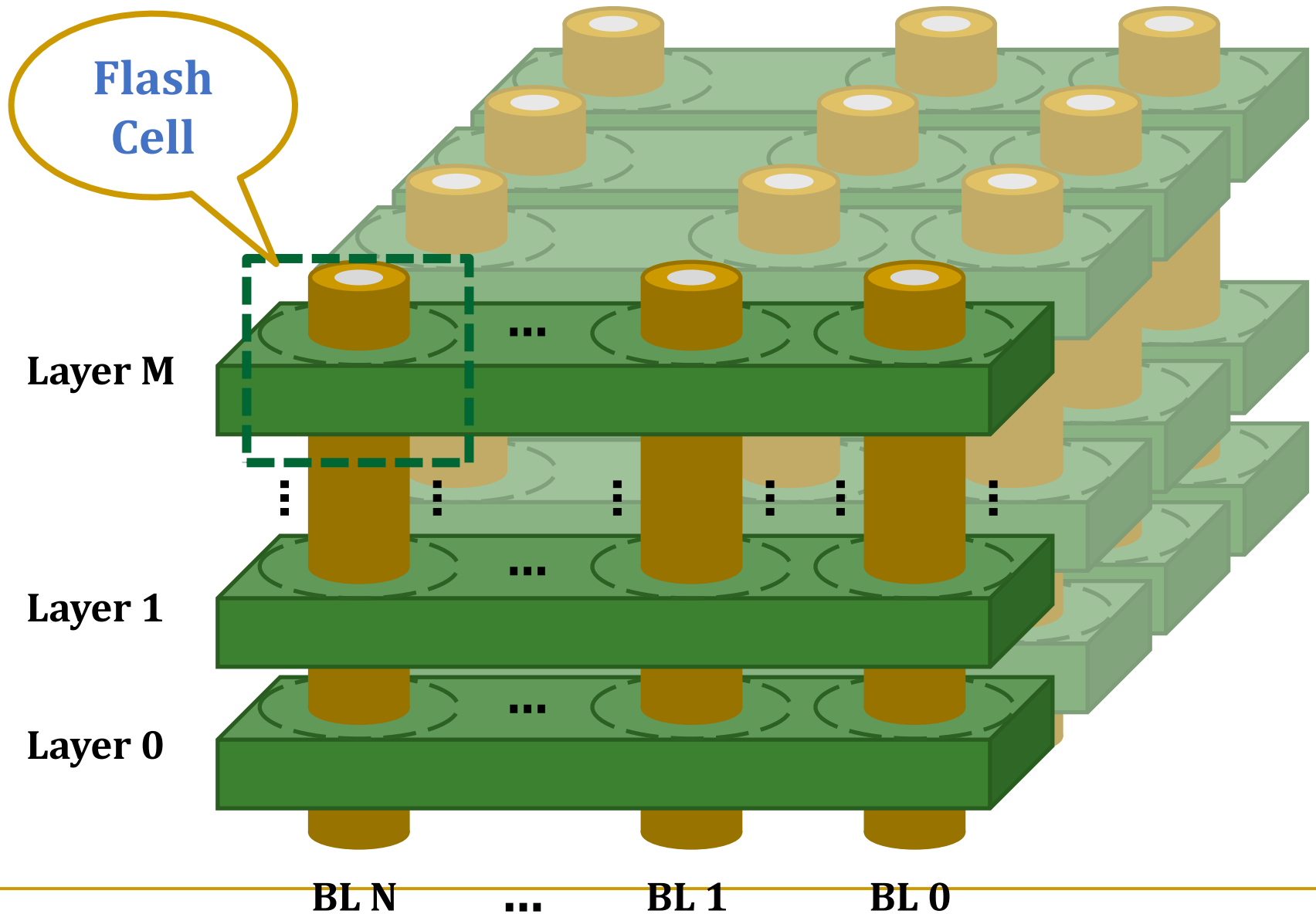
Increase # of layers

## **Reliability**

Scaling hurts reliability

**Not well studied!**

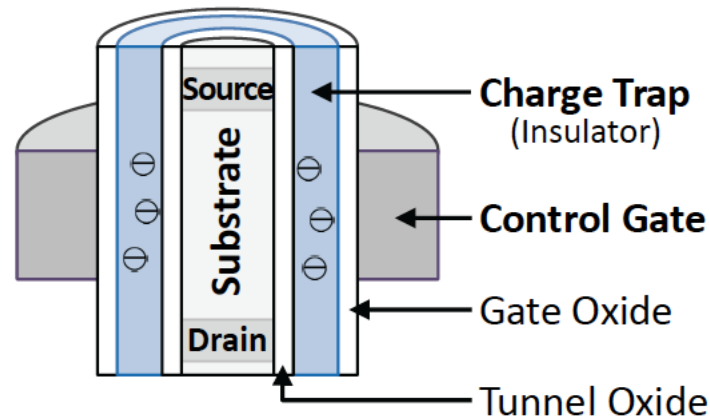
# 3D NAND Flash Memory Structure



# Charge Trap Based 3D Flash Cell

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- Cross-section of a charge trap transistor



# 3D NAND Flash Memory Organization

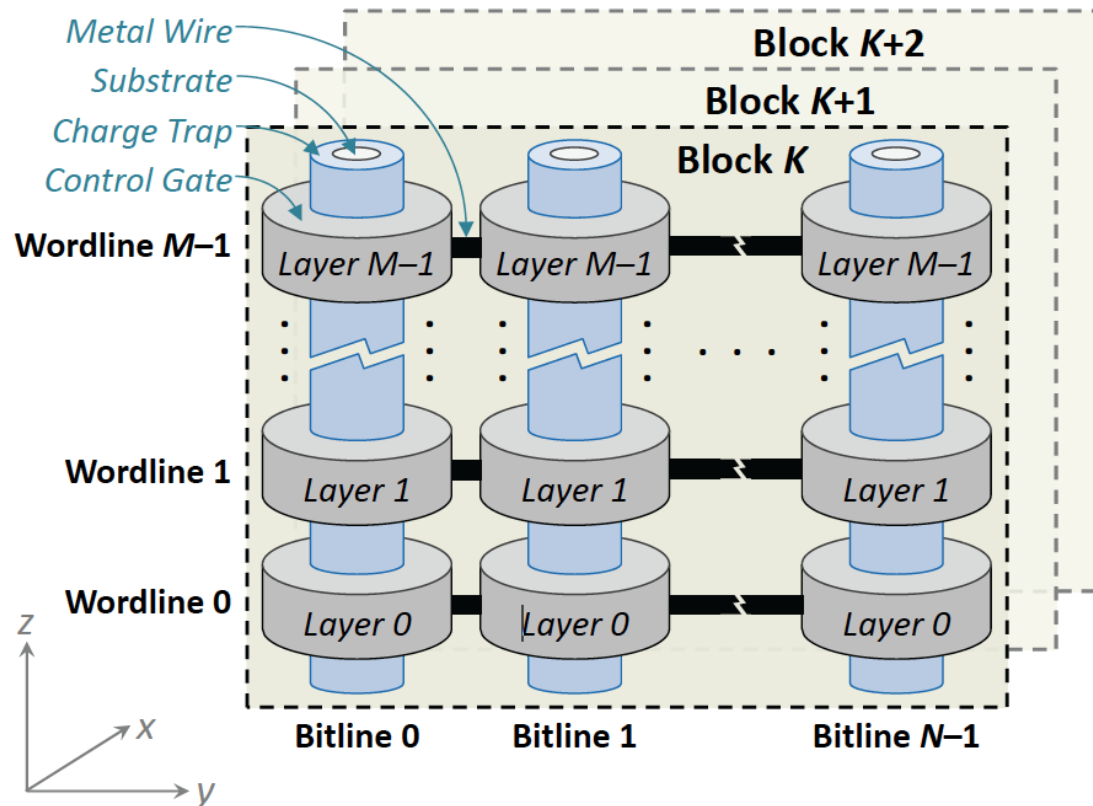


Fig. 43. Organization of flash cells in an  $M$ -layer 3D charge trap NAND flash memory chip, where each block consists of  $M$  wordlines and  $N$  bitlines.



*Proceedings of the IEEE, Sept. 2017*



## Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

*This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.*

By YU CAI, SAUGATA GHOSE, ERICH F. HARATSCH, YIXIN LUO, AND ONUR MUTLU

<https://arxiv.org/pdf/1706.08642>



# More Up-to-date Version

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- Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu, **"Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery"**  
*Invited Book Chapter in Inside Solid State Drives, 2018.*  
[Preliminary arxiv.org version]

## Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery

YU CAI, SAUGATA GHOSE

Carnegie Mellon University

ERICH F. HARATSCH

Seagate Technology

YIXIN LUO

Carnegie Mellon University

ONUR MUTLU

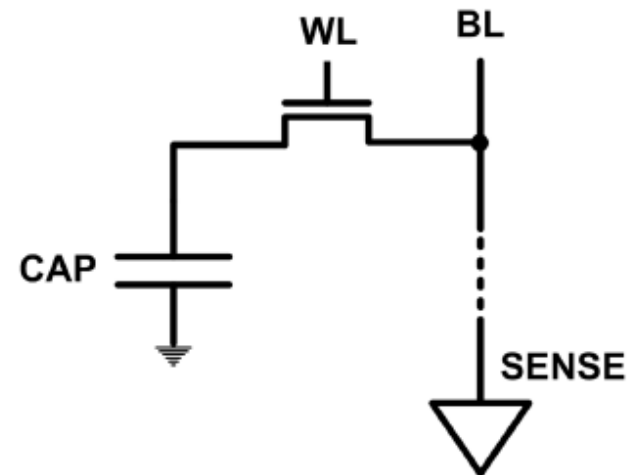
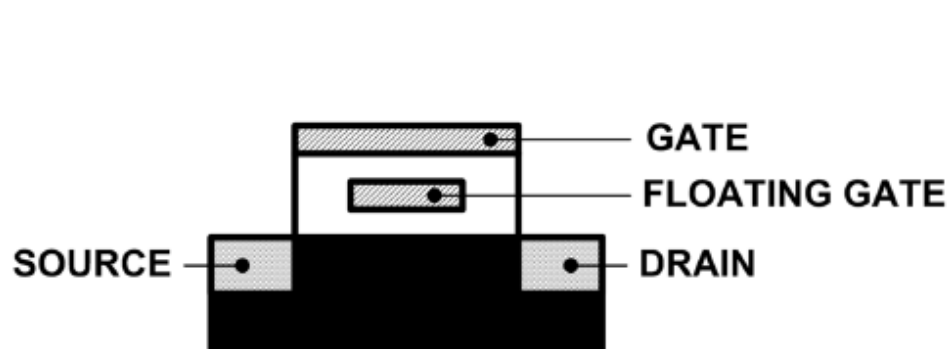
ETH Zürich and Carnegie Mellon University

# Flash Memory Reliability and Security

# Error Analysis and Management of NAND Flash Memory

# Limits of Charge Memory

- Difficult charge placement and control
  - Flash: floating gate charge
  - DRAM: capacitor charge, transistor leakage
- Reliable sensing becomes difficult as charge storage unit size reduces



# Executive Summary

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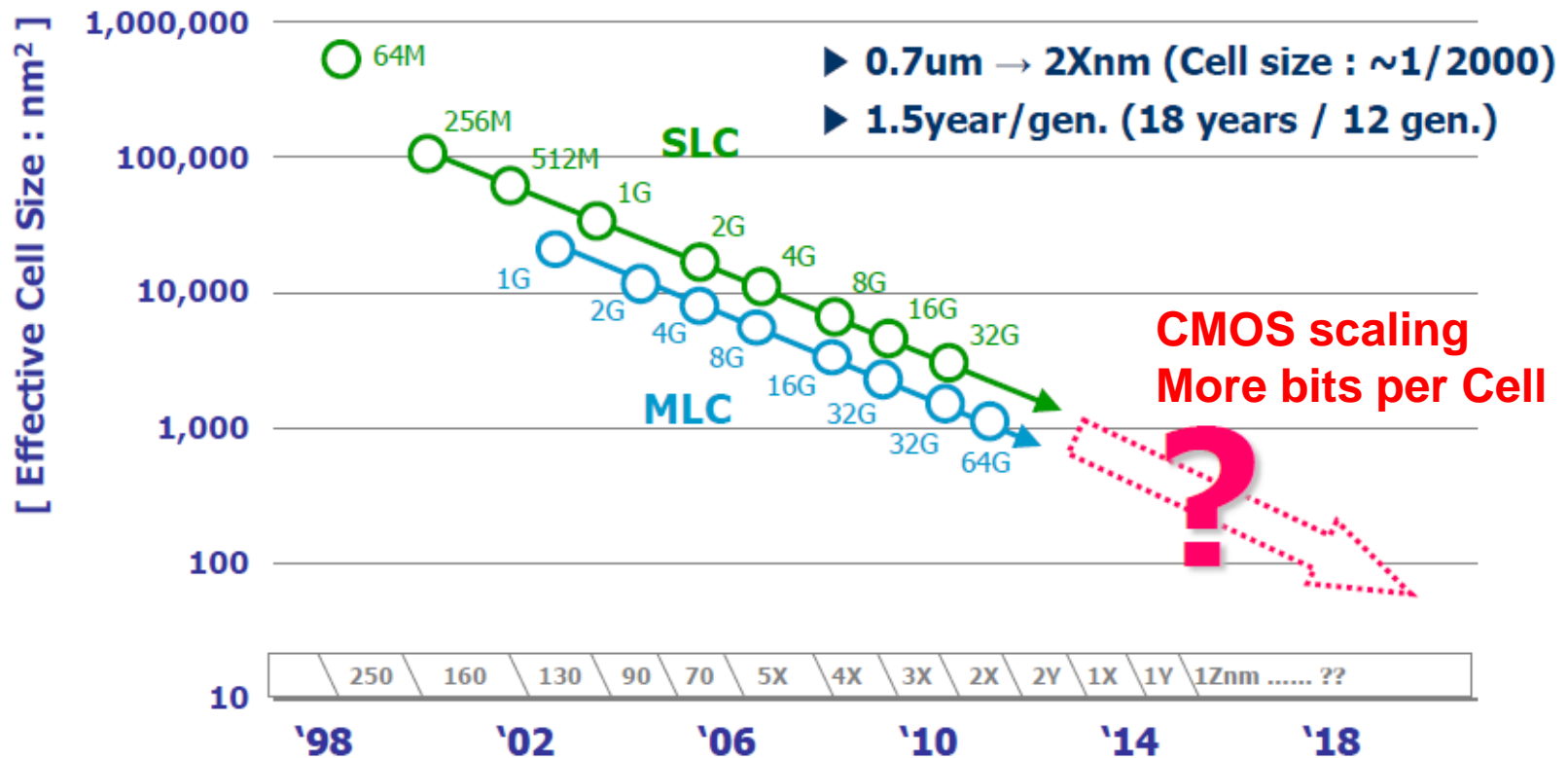
- Problem: MLC NAND flash memory reliability/endurance is a key challenge for satisfying future storage systems' requirements
- Our Goals: (1) Build reliable error models for NAND flash memory via experimental characterization, (2) Develop efficient techniques to improve reliability and endurance
- This lecture provides a “flash” summary of our recent results published in the past 8 years:
  - Experimental error and threshold voltage characterization [DATE'12&13]
  - Retention-aware error management [ICCD'12]
  - Program interference analysis and read reference V prediction [ICCD'13]
  - Neighbor-assisted error correction [SIGMETRICS'14]
  - Read disturb error handling [DSN'15]
  - Data retention error handling [HPCA'15]

# Agenda

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- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Characterization Results
  - Retention-Aware Error Management
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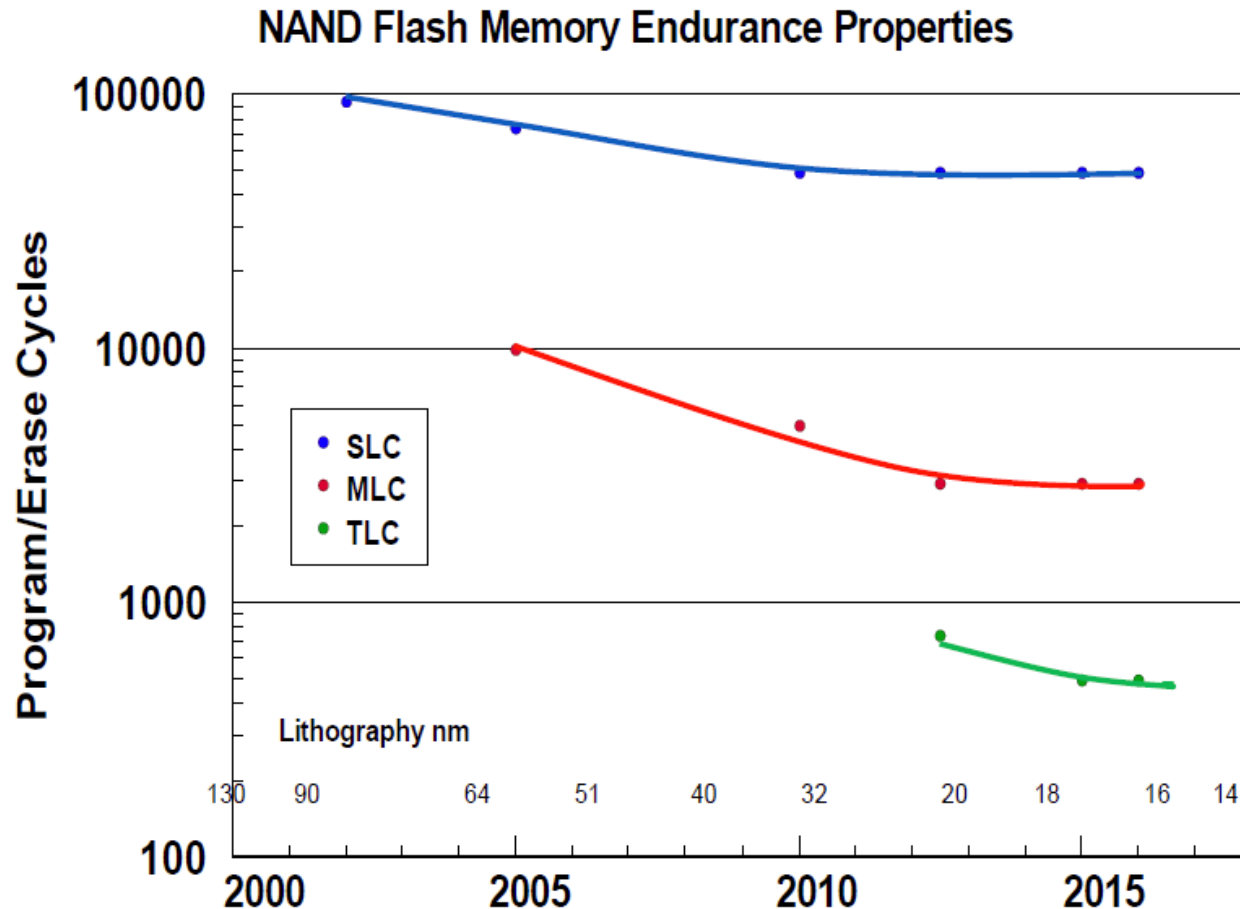
# Evolution of NAND Flash Memory



Seaung Suk Lee, "Emerging Challenges in NAND Flash Technology", Flash Summit 2011 (Hynix)

- Flash memory is widening its range of applications
  - Portable consumer devices, laptop PCs and enterprise servers

# Flash Challenges: Reliability and Endurance



E. Grochowski et al., "Future technology challenges for NAND flash and HDD products", Flash Memory Summit 2012

- **P/E cycles (provided)**

**A few thousand**

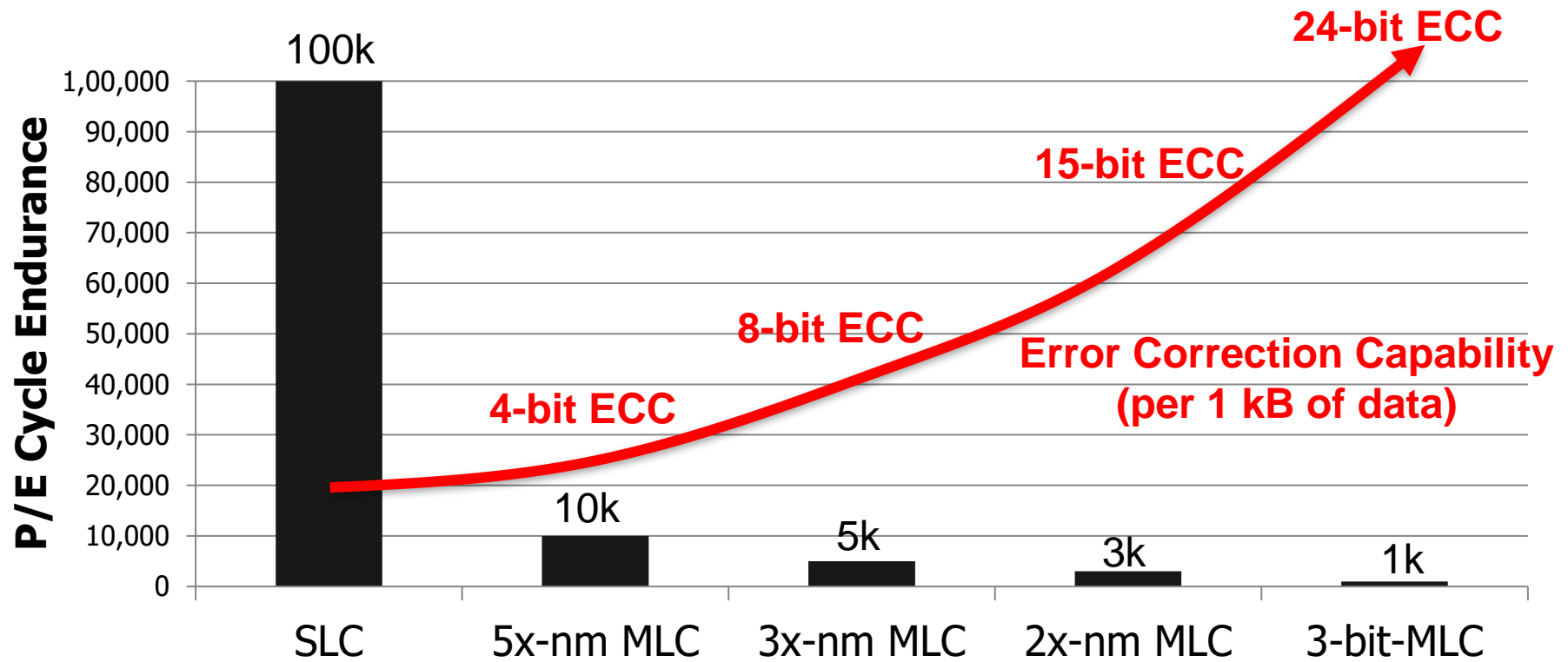
- **P/E cycles (required)**

Writing  
the full capacity  
of the drive  
**10 times per day**  
**for 5 years**  
(STEC)

**> 50k P/E cycles**



# Decreasing Endurance with Flash Scaling



Ariel Maislos, "A New Era in Embedded Flash Memory", Flash Summit 2011 (Anobit)

- Endurance of flash memory decreasing with scaling and multi-level cells
- Error correction capability required to guarantee storage-class reliability ( $UBER < 10^{-15}$ ) is increasing exponentially to reach less endurance

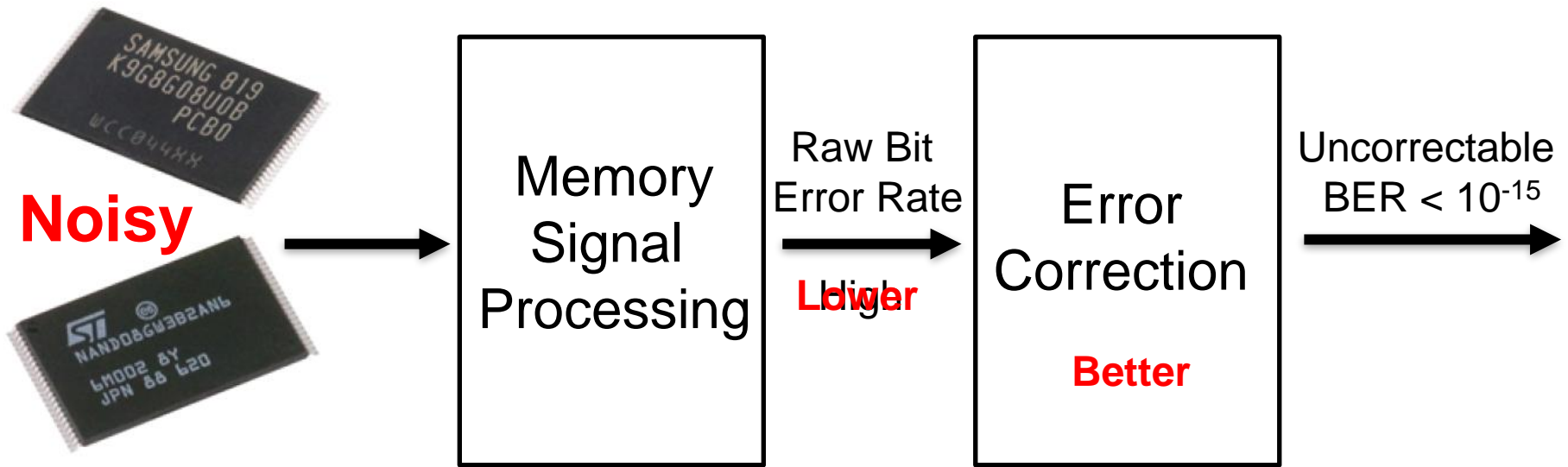
# NAND Flash Memory is Increasingly Noisy

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# Future NAND Flash-based Storage Architecture

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## Our Goals:

Build reliable error models for NAND flash memory

Design efficient reliability mechanisms based on the model

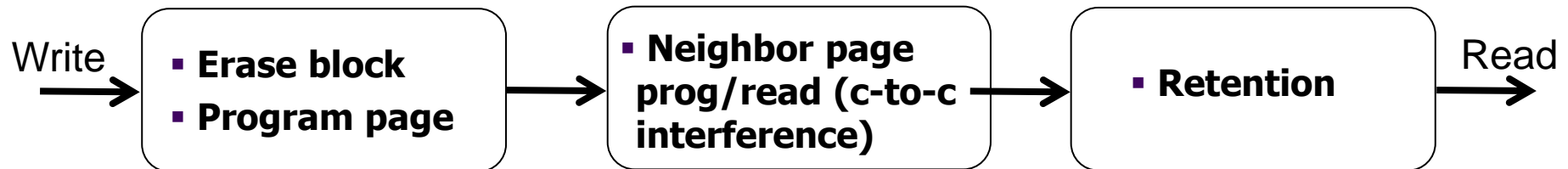
# NAND Flash Error Model



## Experimentally characterize and model dominant errors

Cai et al., "Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis", **DATE 2012**

Luo et al., "Enabling Accurate and Practical Online Flash Channel Modeling for Modern MLC NAND Flash Memory", **JSAC 2016**



Cai et al., "Threshold voltage distribution in MLC NAND Flash Memory: Characterization, Analysis, and Modeling", **DATE 2013**

Cai et al., "Vulnerabilities in MLC NAND Flash Memory Programming: Experimental Analysis, Exploits, and Mitigation Techniques", **HPCA 2017**

Cai et al., "Program Interference in MLC NAND Flash Memory: Characterization, Modeling, and Mitigation", **ICCD 2013**

Cai et al., "Neighbor-Cell Assisted Error Correction in MLC NAND Flash Memories", **SIGMETRICS 2014**

Cai et al., "Read Disturb Errors in MLC NAND Flash Memory: Characterization and Mitigation", **DSN 2015**

Cai et al., "Flash Correct-and-Refresh: Retention-aware error management for increased flash memory lifetime", **ICCD 2012**

Cai et al., "Error Analysis and Retention-Aware Error Management for NAND Flash Memory", **ITJ 2013**

Cai et al., "Data Retention in MLC NAND Flash Memory: Characterization, Optimization and Recovery", **HPCA 2015**

# Our Goals and Approach

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## ■ Goals:

- Understand error mechanisms and develop reliable predictive models for MLC NAND flash memory errors
- Develop efficient error management techniques to mitigate errors and improve flash reliability and endurance

## ■ Approach:

- Solid experimental analyses of errors in real MLC NAND flash memory → drive the understanding and models
- Understanding, models, and creativity → drive the new techniques

# Many Errors and Their Mitigation [PIEEE'17]

**Table 3** List of Different Types of Errors Mitigated by NAND Flash Error Mitigation Mechanisms

Mitigation Mechanism	Error Type				
	<i>P/E Cycling</i> [32,33,42] (§IV-A)	<i>Program</i> [40,42,53] (§IV-B)	<i>Cell-to-Cell Interference</i> [32,35,36,55] (§IV-C)	<i>Data Retention</i> [20,32,34,37,39] (§IV-D)	<i>Read Disturb</i> [20,32,38,62] (§IV-E)
<b>Shadow Program Sequencing</b> [35,40] (Section V-A)			X		
<b>Neighbor-Cell Assisted Error Correction</b> [36] (Section V-B)			X		
<b>Refresh</b> [34,39,67,68] (Section V-C)				X	X
<b>Read-Retry</b> [33,72,107] (Section V-D)	X			X	X
<b>Voltage Optimization</b> [37,38,74] (Section V-E)	X			X	X
<b>Hot Data Management</b> [41,63,70] (Section V-F)	X	X	X	X	X
<b>Adaptive Error Mitigation</b> [43,65,77,78,82] (Section V-G)	X	X	X	X	X

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.



*Proceedings of the IEEE, Sept. 2017*



## Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

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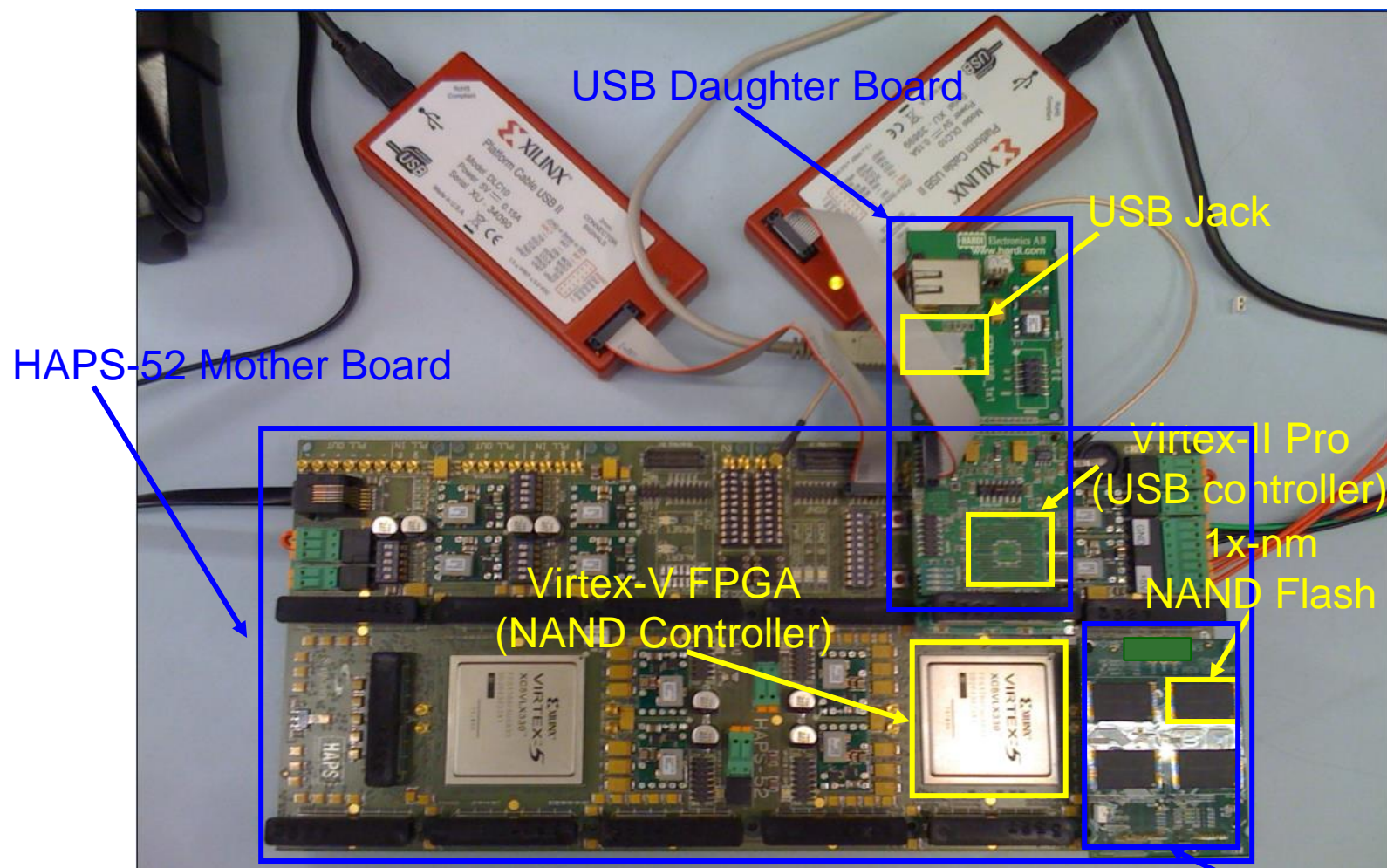


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# Experimental Testing Platform



[DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, HPCA 2015, DSN 2015, MSST 2015, JSAC 2016, HPCA 2017, DFRWS 2017, PIEEE 2017, HPCA 2018, SIGMETRICS 2018]

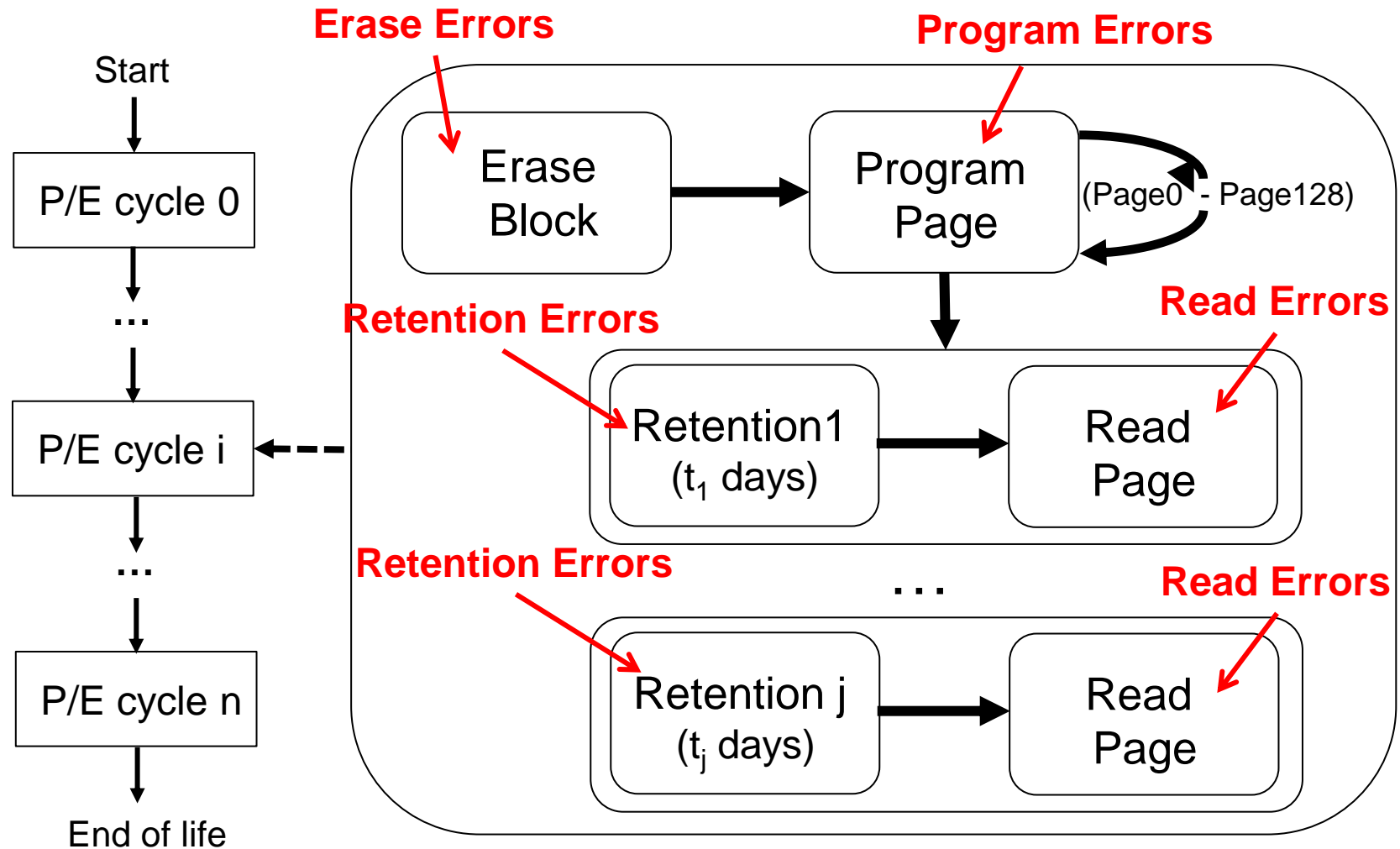
Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.

# NAND Flash Error Types

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- Four types of errors [Cai+, DATE 2012]
- Caused by common flash operations
  - ❑ Read errors
  - ❑ Erase errors
  - ❑ Program (interference) errors
- Caused by flash cell losing charge over time
  - ❑ Retention errors
    - Whether an error happens depends on required retention time
    - Especially problematic in MLC flash because threshold voltage window to determine stored value is smaller

# NAND Flash Usage and Error Model



# Methodology: Error and ECC Analysis

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- **Characterized errors and error rates** of 3x and 2y-nm MLC NAND flash using an experimental FPGA-based platform
  - [Cai+, DATE'12, ICCD'12, DATE'13, ITJ'13, ICCD'13, SIGMETRICS'14]
- **Quantified Raw Bit Error Rate (RBER) at a given P/E cycle**
  - Raw Bit Error Rate: Fraction of erroneous bits without any correction
- **Quantified error correction capability** (and area and power consumption) of various BCH-code implementations
  - Identified how much RBER each code can tolerate
    - how many P/E cycles (flash lifetime) each code can sustain

# Agenda

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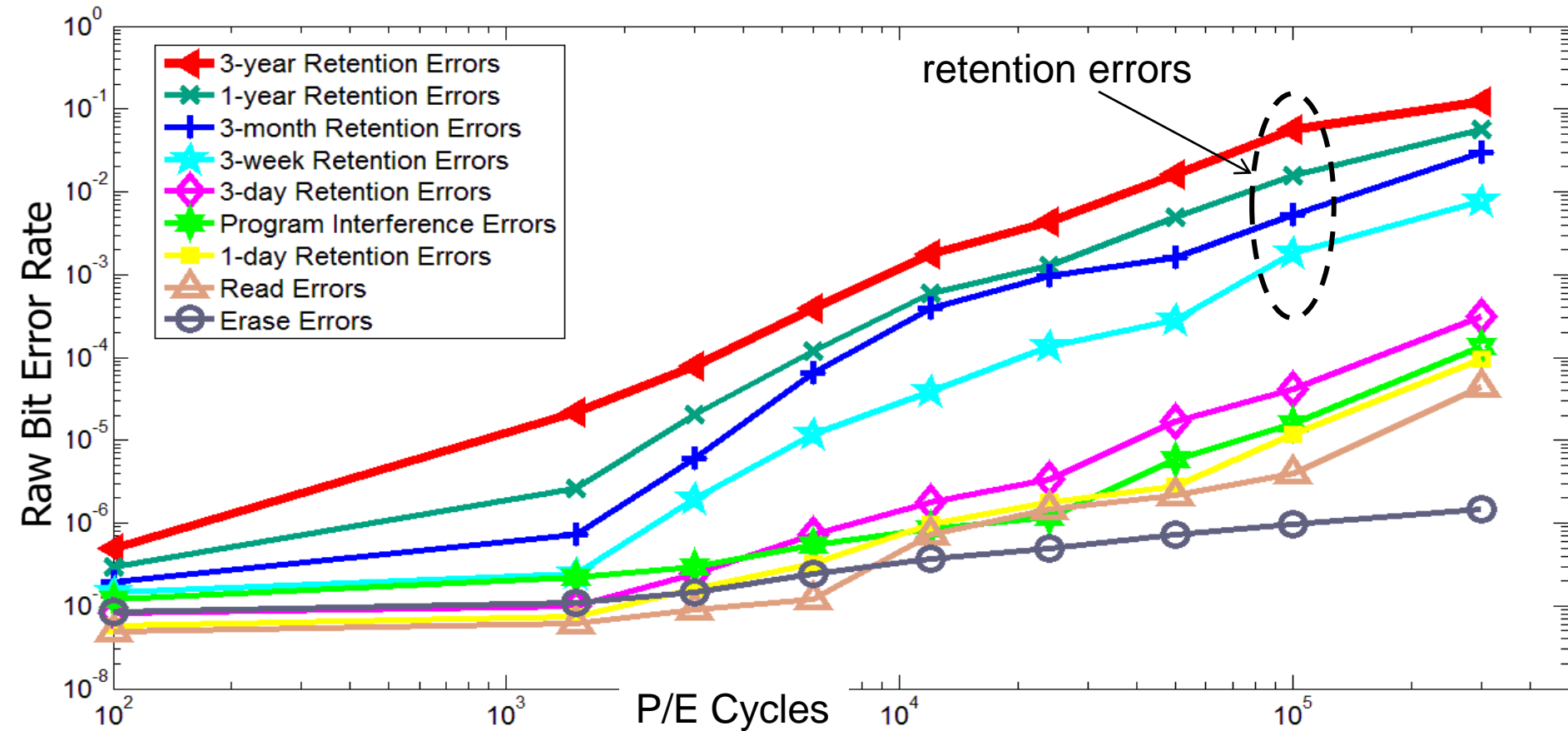
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# Error Types and Testing Methodology

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- Erase errors
    - Count the number of cells that fail to be erased to “11” state
  - Program interference errors
    - Compare the data immediately after page programming and the data after the whole block being programmed
  - Read errors
    - Continuously read a given block and compare the data between consecutive read sequences
  - Retention errors
    - Compare the data read after an amount of time to data written
      - Characterize short term retention errors under room temperature
      - Characterize long term retention errors by baking in the oven under 125°C
-

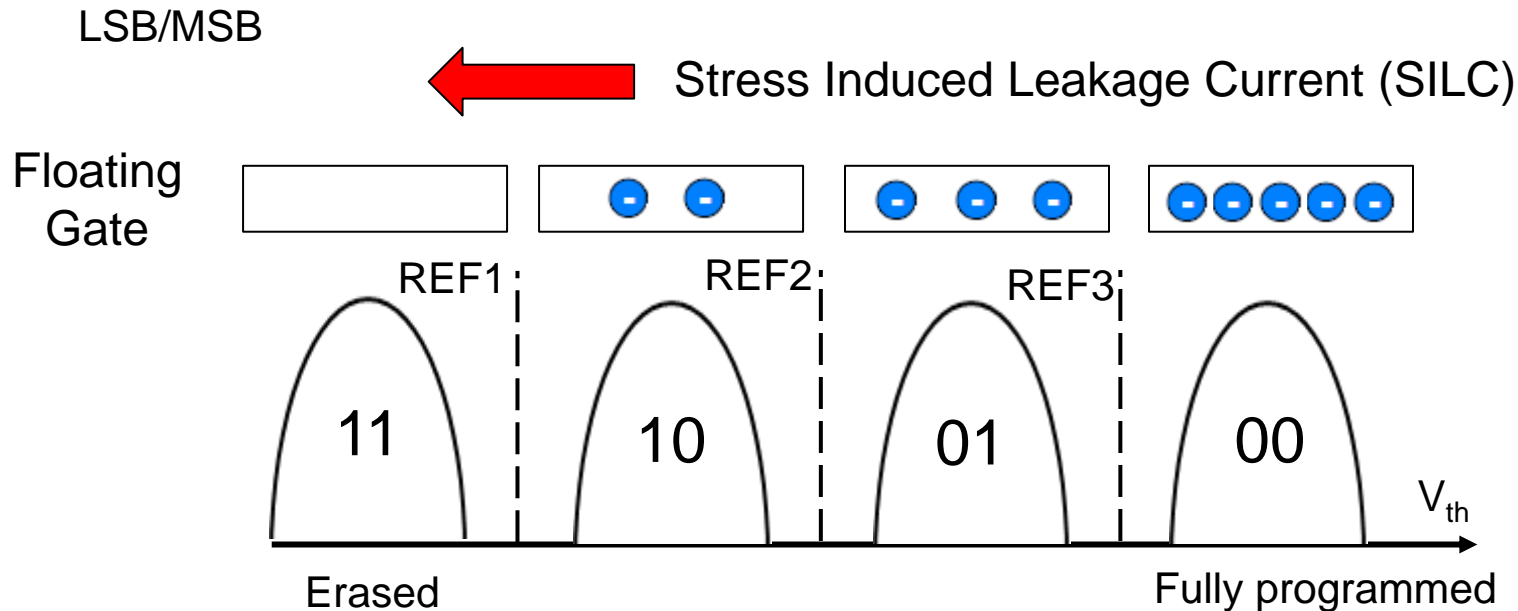
# Observations: Flash Error Analysis



- Raw bit error rate increases exponentially with P/E cycles
- Retention errors are dominant (>99% for 1-year ret. time)
- Retention errors increase with retention time requirement

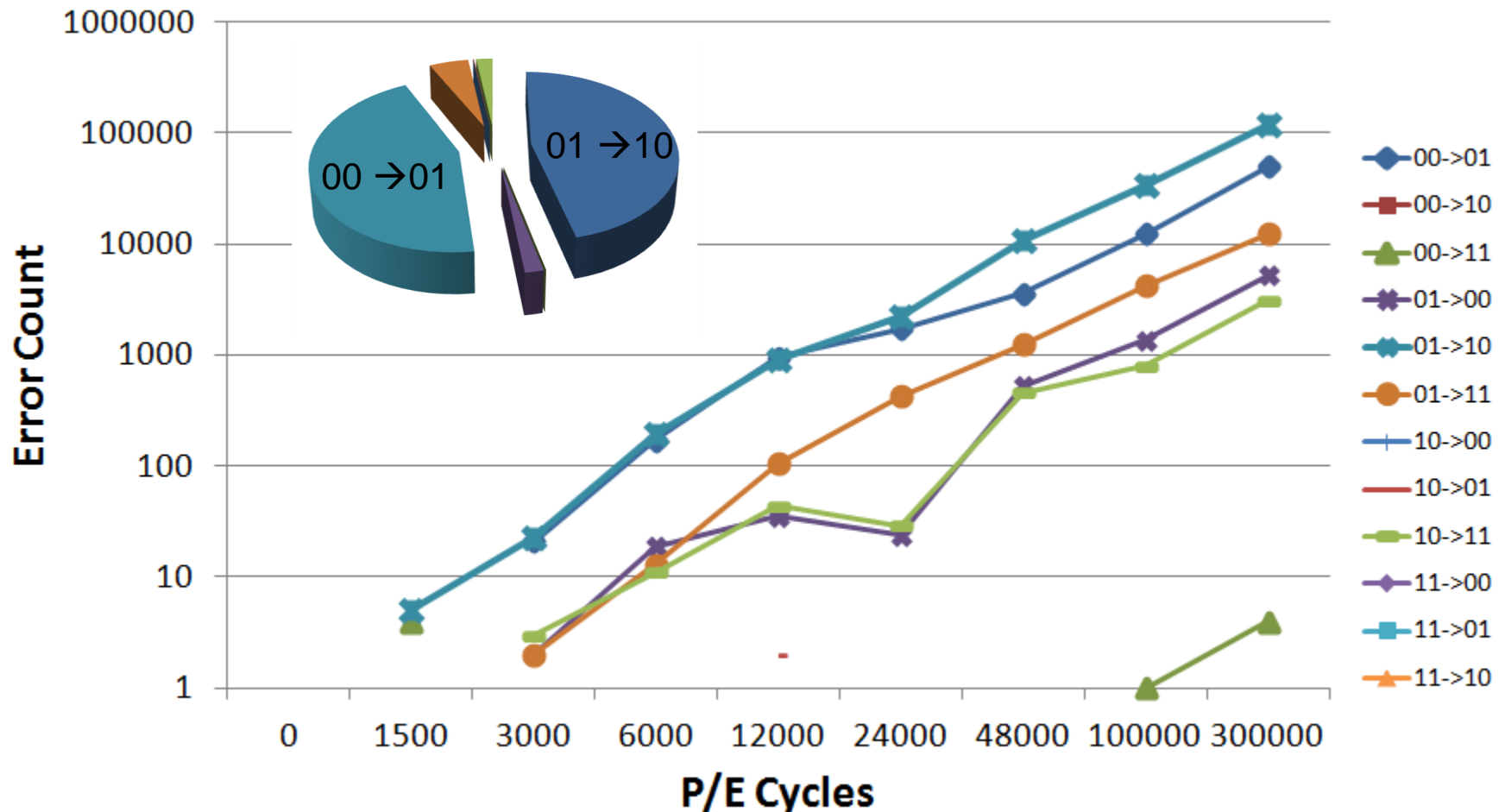


# Retention Error Mechanism



- Electron loss from the floating gate causes retention errors
  - ❑ Cells with more programmed electrons suffer more from retention errors
  - ❑ Threshold voltage is more likely to shift by one window than by multiple

# Retention Error Value Dependency



- Cells with more programmed electrons tend to suffer more from retention noise (i.e. 00 and 01)

# More on Flash Error Analysis

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- Yu Cai, Erich F. Haratsch, Onur Mutlu, and Ken Mai, **"Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis"** *Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Dresden, Germany, March 2012. Slides (ppt)*

## Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis

Yu Cai<sup>1</sup>, Erich F. Haratsch<sup>2</sup>, Onur Mutlu<sup>1</sup> and Ken Mai<sup>1</sup>

<sup>1</sup>Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA

<sup>2</sup>LSI Corporation, 1110 American Parkway NE, Allentown, PA

<sup>1</sup>{yucai, onur, kenmai}@andrew.cmu.edu, <sup>2</sup>erich.haratsch@lsi.com

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# Solution to Retention Errors

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- Refresh periodically
- Change the period based on P/E cycle wearout
  - Refresh more often at higher P/E cycles
- Use a combination of **in-place** and **remapping-based** refresh
- Cai et al. “**Flash Correct-and-Refresh: Retention-Aware Error Management for Increased Flash Memory Lifetime**”, ICCD 2012.

# Flash Correct-and-Refresh (FCR)

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## ■ Key Observations:

- ❑ Retention errors are the dominant source of errors in flash memory [Cai+ DATE 2012][Tanakamaru+ ISSCC 2011]  
→ limit flash lifetime as they increase over time
- ❑ Retention errors can be corrected by “refreshing” each flash page periodically

## ■ Key Idea:

- ❑ Periodically read each flash page,
- ❑ Correct its errors using “weak” ECC, and
- ❑ Either remap it to a new physical page or reprogram it in-place,
- ❑ Before the page accumulates more errors than ECC-correctable
- ❑ Optimization: Adapt refresh rate to endured P/E cycles

# FCR: Two Key Questions

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## ■ How to refresh?

- ❑ Remap a page to another one
- ❑ Reprogram a page (in-place)
- ❑ Hybrid of remap and reprogram

## ■ When to refresh?

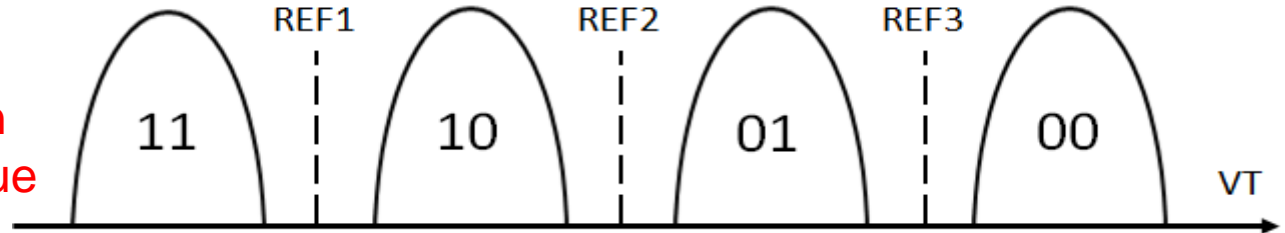
- ❑ Fixed period
- ❑ Adapt the period to retention error severity

# In-Place Reprogramming of Flash Cells

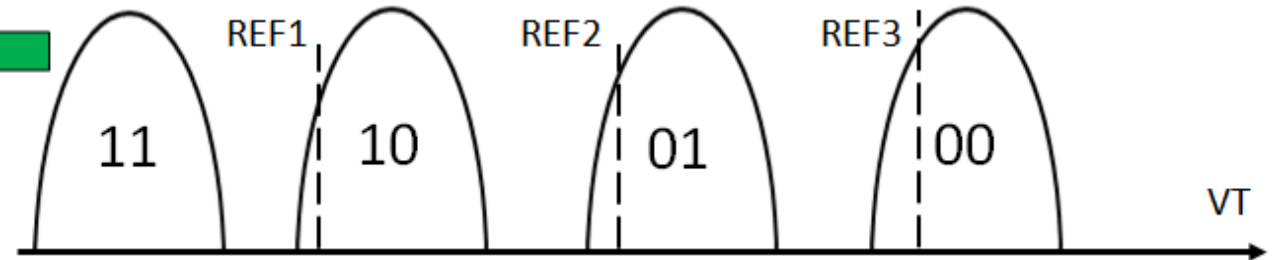
Floating Gate



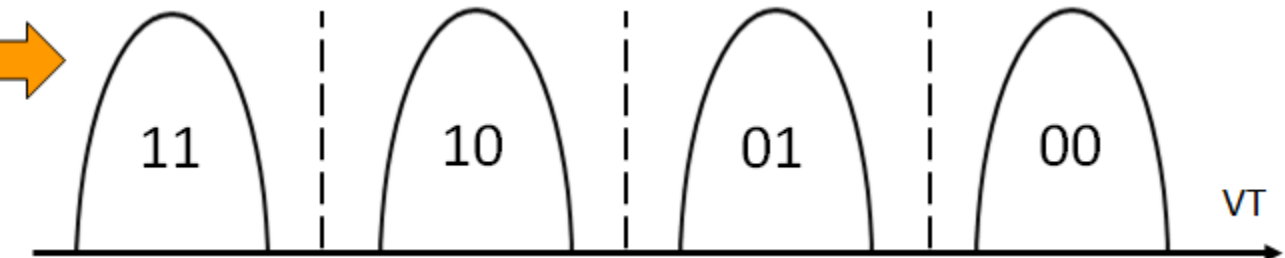
Floating Gate  
Voltage Distribution  
for each Stored Value



Retention errors are  
caused by cell voltage  
shifting to the left



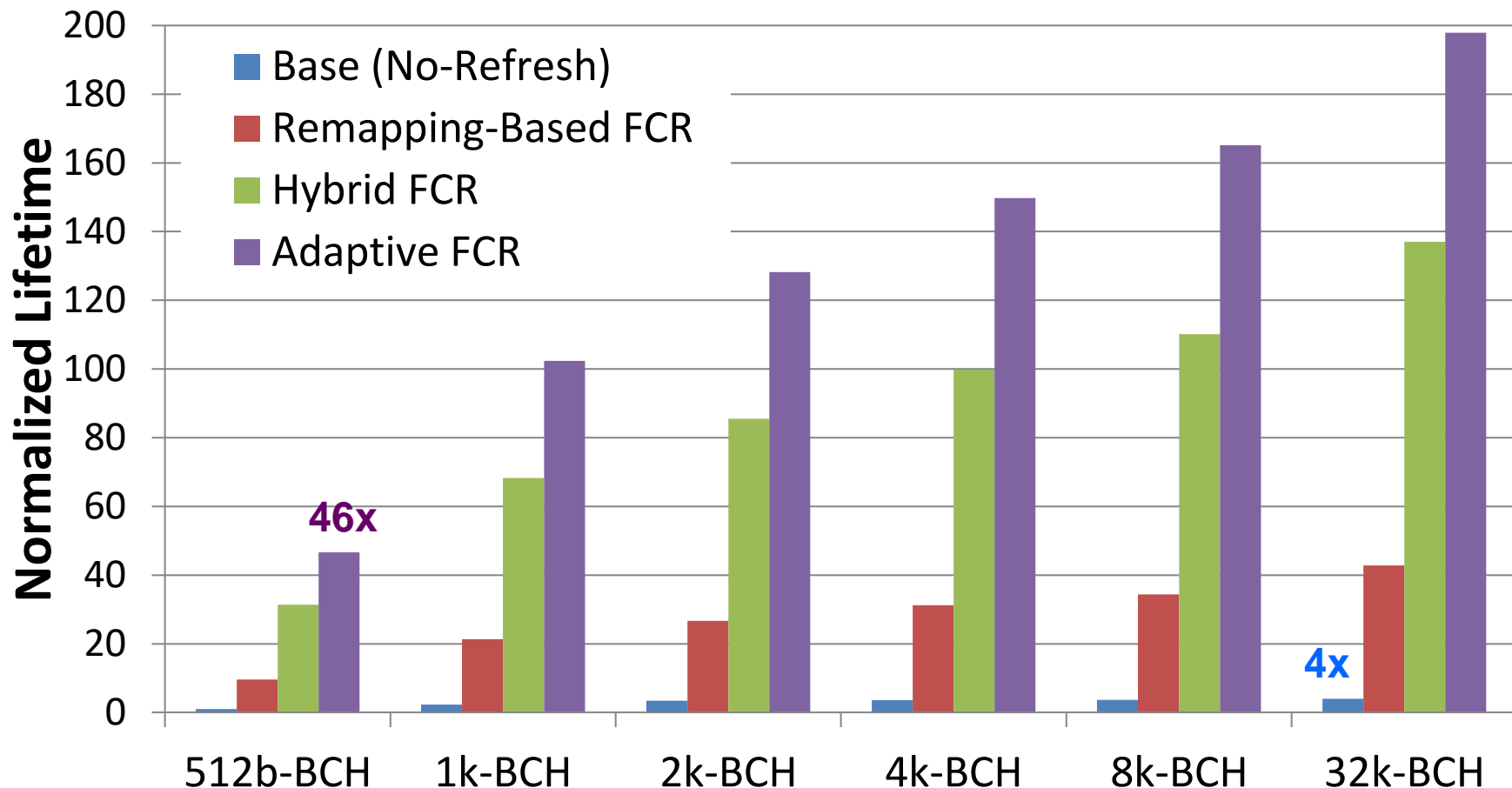
ISPP moves cell  
voltage to the right;  
fixes retention errors



- Pro: No remapping needed → no additional erase operations
- Con: Increases the occurrence of program errors



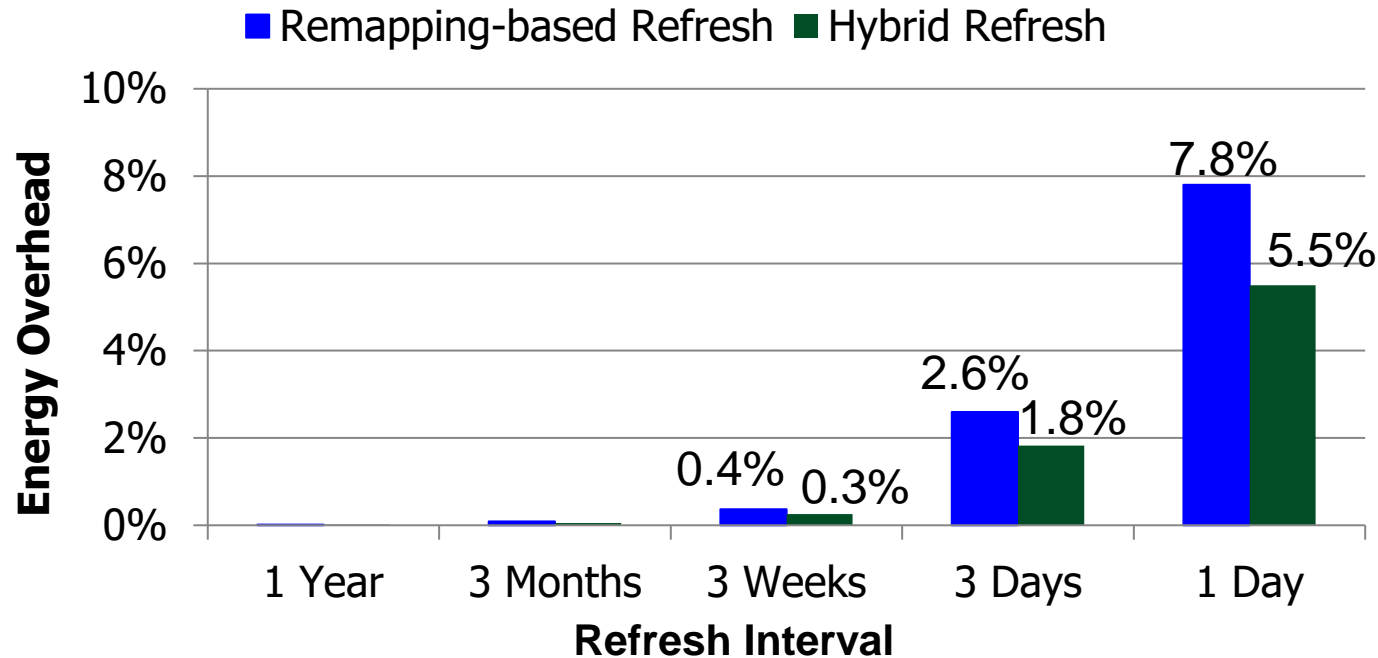
# Normalized Flash Memory Lifetime



**Adaptive-rate FCR provides the highest lifetime**

**Lifetime of FCR much higher than lifetime of stronger ECC**

# Energy Overhead



- Adaptive-rate refresh: <1.8% energy increase until daily refresh is triggered

# Flash Correct-and-Refresh [ICCD'12]

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- Yu Cai, Gulay Yalcin, Onur Mutlu, Erich F. Haratsch, Adrian Cristal, Osman Unsal, and Ken Mai,  
**"Flash Correct-and-Refresh: Retention-Aware Error Management for Increased Flash Memory Lifetime"**  
*Proceedings of the 30th IEEE International Conference on Computer Design (ICCD)*, Montreal, Quebec, Canada, September 2012. [Slides \(ppt\)\(pdf\)](#)

## Flash Correct-and-Refresh: Retention-Aware Error Management for Increased Flash Memory Lifetime

Yu Cai<sup>1</sup>, Gulay Yalcin<sup>2</sup>, Onur Mutlu<sup>1</sup>, Erich F. Haratsch<sup>3</sup>, Adrian Cristal<sup>2</sup>, Osman S. Unsal<sup>2</sup> and Ken Mai<sup>1</sup>

<sup>1</sup>DSSC, Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA

<sup>2</sup>Barcelona Supercomputing Center, C/Jordi Girona 29, Barcelona, Spain

<sup>3</sup>LSI Corporation, 1110 American Parkway NE, Allentown, PA

# More Detail on Flash Error Analysis

---

- Yu Cai, Gulay Yalcin, Onur Mutlu, Erich F. Haratsch, Adrian Cristal, Osman Unsal, and Ken Mai,  
**"Error Analysis and Retention-Aware Error Management for NAND Flash Memory"**  
*Intel Technology Journal (ITJ) Special Issue on Memory Resiliency*, Vol. 17, No. 1, May 2013.

Intel® Technology Journal | Volume 17, Issue 1, 2013

ERROR ANALYSIS AND RETENTION-AWARE ERROR MANAGEMENT  
FOR NAND FLASH MEMORY

# Many Errors and Their Mitigation [PIEEE'17]

**Table 3** List of Different Types of Errors Mitigated by NAND Flash Error Mitigation Mechanisms

Mitigation Mechanism	Error Type				
	<i>P/E Cycling</i> [32,33,42] (§IV-A)	<i>Program</i> [40,42,53] (§IV-B)	<i>Cell-to-Cell Interference</i> [32,35,36,55] (§IV-C)	<i>Data Retention</i> [20,32,34,37,39] (§IV-D)	<i>Read Disturb</i> [20,32,38,62] (§IV-E)
<b>Shadow Program Sequencing</b> [35,40] (Section V-A)			X		
<b>Neighbor-Cell Assisted Error Correction</b> [36] (Section V-B)			X		
<b>Refresh</b> [34,39,67,68] (Section V-C)				X	X
<b>Read-Retry</b> [33,72,107] (Section V-D)	X			X	X
<b>Voltage Optimization</b> [37,38,74] (Section V-E)	X			X	X
<b>Hot Data Management</b> [41,63,70] (Section V-F)	X	X	X	X	X
<b>Adaptive Error Mitigation</b> [43,65,77,78,82] (Section V-G)	X	X	X	X	X

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.



*Proceedings of the IEEE, Sept. 2017*



## Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

*This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.*

By YU CAI, SAUGATA GHOSE, ERICH F. HARATSCH, YIXIN LUO, AND ONUR MUTLU

<https://arxiv.org/pdf/1706.08642>

# More Up-to-date Version

---

- Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu, **"Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery"**  
*Invited Book Chapter in Inside Solid State Drives, 2018.*  
[Preliminary arxiv.org version]

## **Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery**

YU CAI, SAUGATA GHOSE

Carnegie Mellon University

ERICH F. HARATSCH

Seagate Technology

YIXIN LUO

Carnegie Mellon University

ONUR MUTLU

ETH Zürich and Carnegie Mellon University

# Agenda

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- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Main Characterization Results
  - Retention-Aware Error Management
  - Threshold Voltage and Program Interference Analysis
  - Read Reference Voltage Prediction
  - Neighbor-Assisted Error Correction
  - Read Disturb Error Handling
  - Retention Error Handling
  - 3D NAND Flash Memory Reliability
- Summary



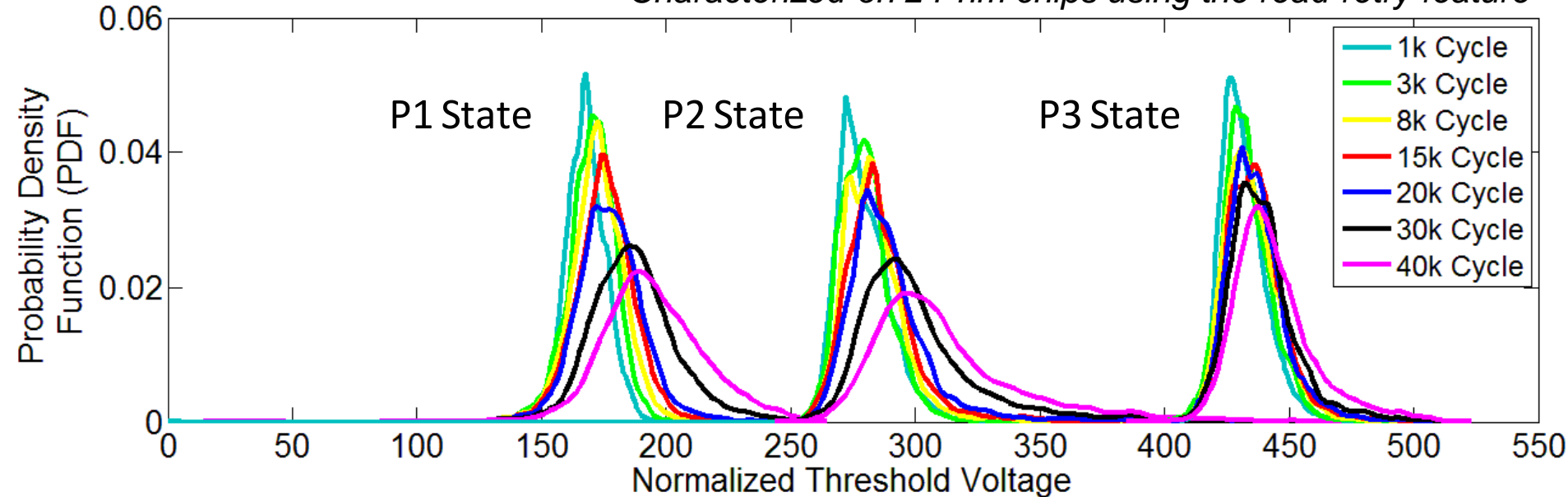
# Key Questions

---

- How does threshold voltage ( $V_{th}$ ) distribution of different programmed states change over flash lifetime?
- Can we model it accurately and predict the  $V_{th}$  changes?
- Can we build mechanisms that can correct for  $V_{th}$  changes? (thereby reducing read error rates)

# Threshold Voltage Distribution Model

*Characterized on 2Y-nm chips using the read-retry feature*



Gaussian distribution with additive white noise

As P/E cycles increase ...

- Distribution shifts to the right
- Distribution becomes wider

# Threshold Voltage Distribution Model

---

- **Vth distribution** can be modeled with  $\sim 95\%$  accuracy as a Gaussian distribution with additive white noise
- **Distortion in Vth** over P/E cycles can be modeled and predicted as **an exponential function of P/E cycles**
  - With more than 95% accuracy

# More Detail on Threshold Voltage Model

---

- Yu Cai, Erich F. Haratsch, Onur Mutlu, and Ken Mai, **"Threshold Voltage Distribution in MLC NAND Flash Memory: Characterization, Analysis and Modeling"** *Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Grenoble, France, March 2013. Slides (ppt)*

## Threshold Voltage Distribution in MLC NAND Flash Memory: Characterization, Analysis, and Modeling

Yu Cai<sup>1</sup>, Erich F. Haratsch<sup>2</sup>, Onur Mutlu<sup>1</sup> and Ken Mai<sup>1</sup>

<sup>1</sup>DSSC, Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA

<sup>2</sup>LSI Corporation, 1110 American Parkway NE, Allentown, PA

<sup>1</sup>{yucai, onur, kenmai}@andrew.cmu.edu, <sup>2</sup>erich.haratsch@lsi.com

# More Accurate and Online Channel Modeling

---

- Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, and Onur Mutlu,  
**"Enabling Accurate and Practical Online Flash Channel Modeling  
for Modern MLC NAND Flash Memory"**  
*to appear in IEEE Journal on Selected Areas in Communications (**JSAC**),  
2016.*

## Enabling Accurate and Practical Online Flash Channel Modeling for Modern MLC NAND Flash Memory

Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, Onur Mutlu

# Non-Gaussian $V_{th}$ Distributions (1X-nm)

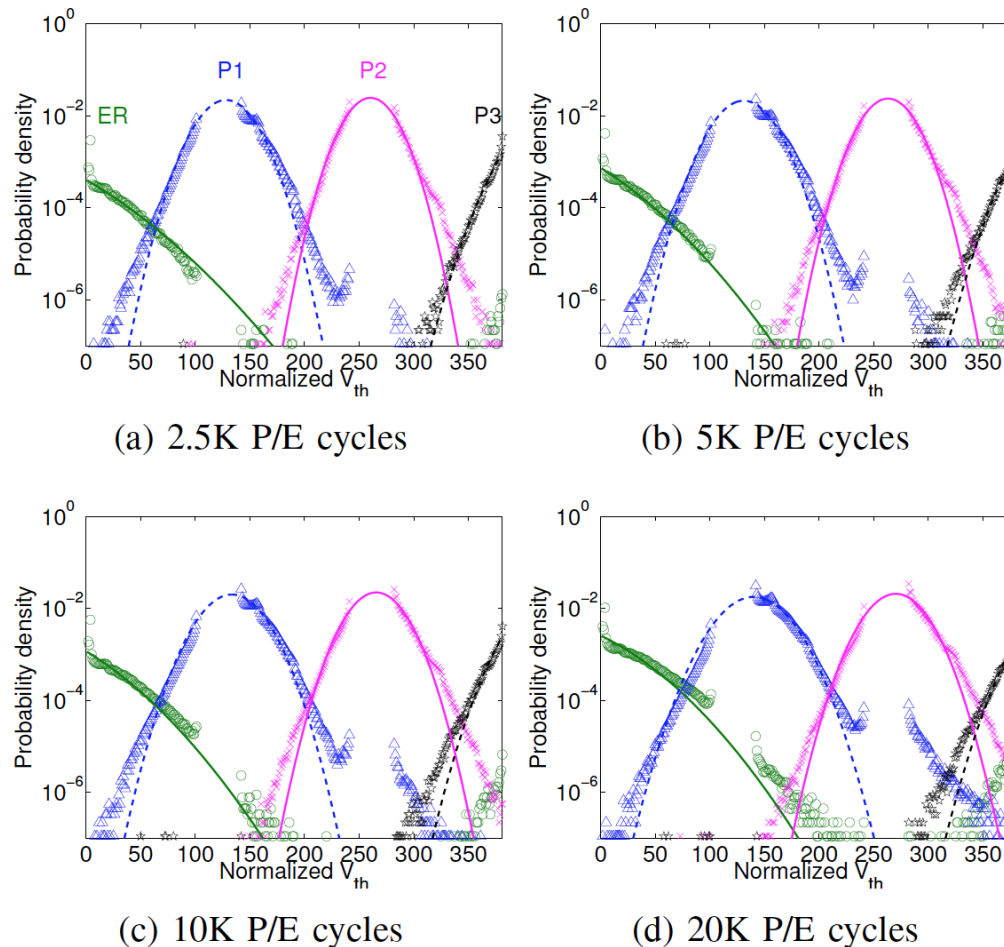


Fig. 4: Gaussian-based model (solid/dashed lines) vs. data measured from real NAND flash chips (markers) under different P/E cycle counts.

# Better Modeling of $V_{th}$ Distributions (I)

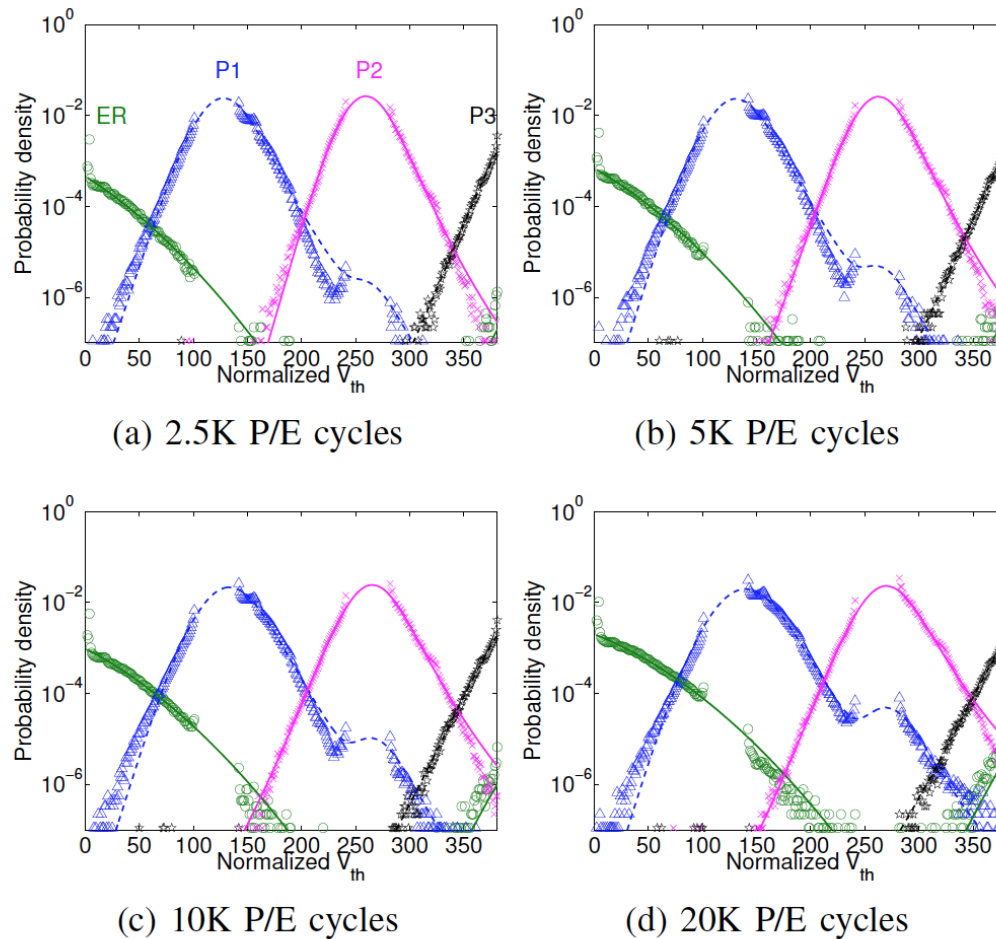


Fig. 6: Our new Student's t-based model (solid/dashed lines) vs. data measured from real NAND flash chips (markers) under different P/E cycle counts.

# Better Modeling of Vth Distributions (II)

---

P/E Cycles	0	2.5K	5K	7.5K	10K	12K	14K	16K	18K	20K	AVG
<b>Gaussian</b>	.99%	1.8%	1.6%	1.8%	1.9%	2.4%	3.1%	8.7%	2.1%	2.3%	<b>2.6%</b>
<b>Normal-Laplace</b>	.34%	.46%	.55%	.61%	.63%	.67%	.68%	.70%	.67%	.67%	<b>.61%</b>
<b>Student's t</b>	.37%	.51%	.61%	.68%	.70%	.76%	.76%	.78%	.76%	.78%	<b>.68%</b>

TABLE 1: Modeling error of the evaluated threshold voltage distribution models, at various P/E cycle counts.



# Prediction vs. Reality with Better Modeling

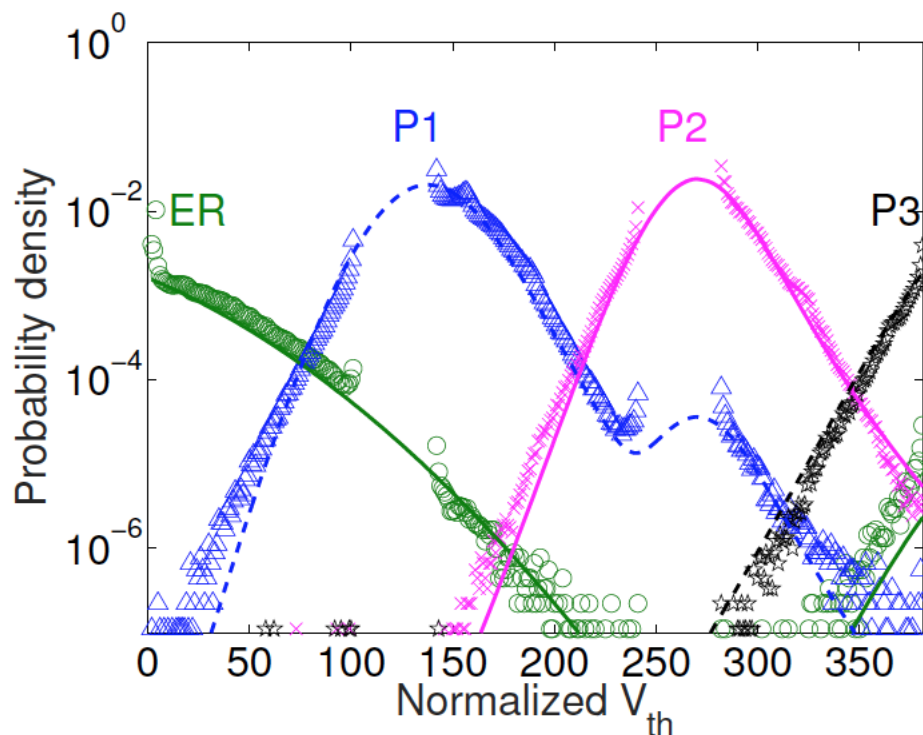


Fig. 13: Threshold voltage distribution as predicted by our dynamic model for 20K P/E cycles, using characterization data from 2.5K, 5K, 7.5K, and 10K P/E cycles, shown as solid/dashed lines. Markers represent data measured from real NAND flash chips at 20K P/E cycles.

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Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, Onur Mutlu

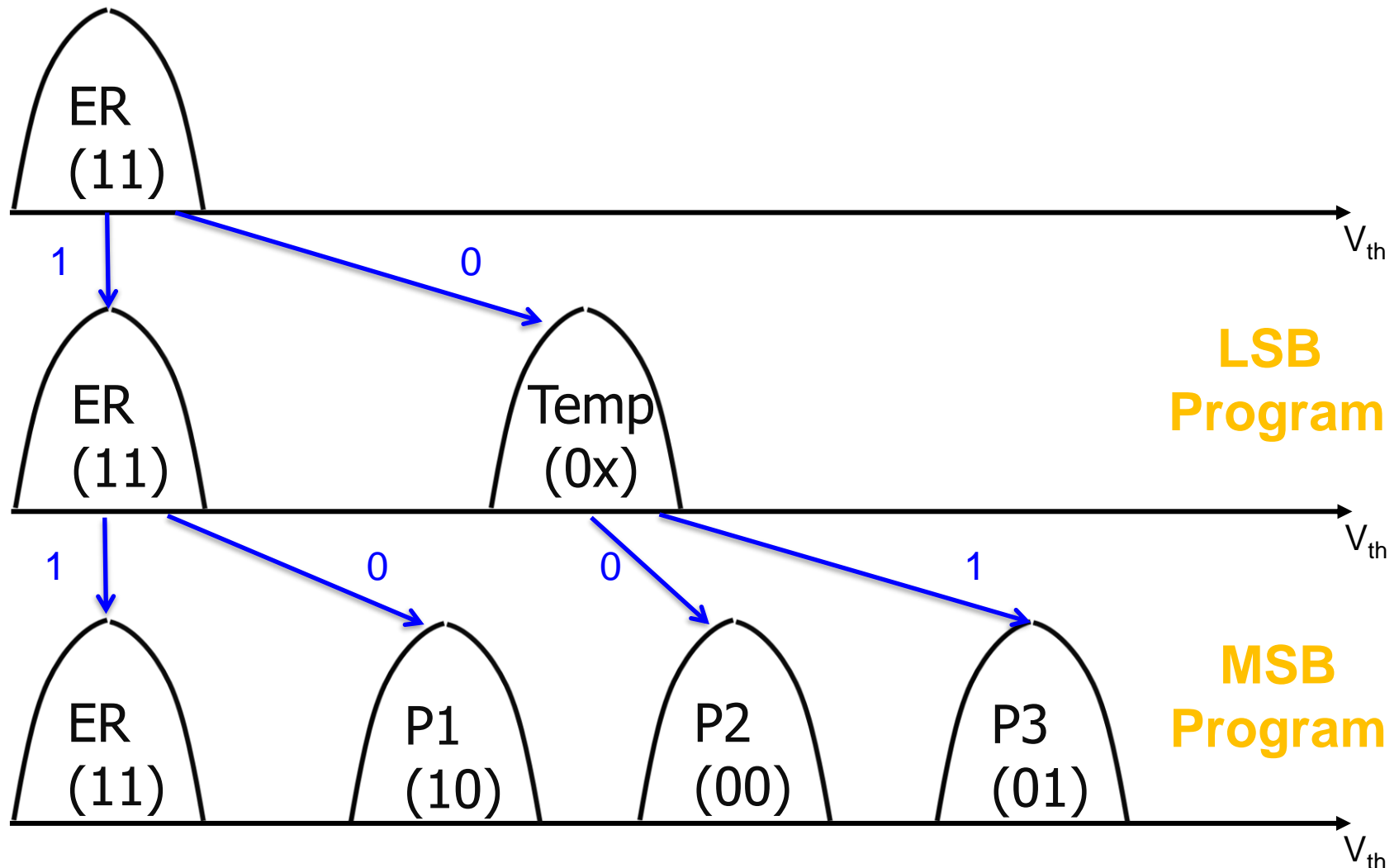
# Program Interference Errors

---

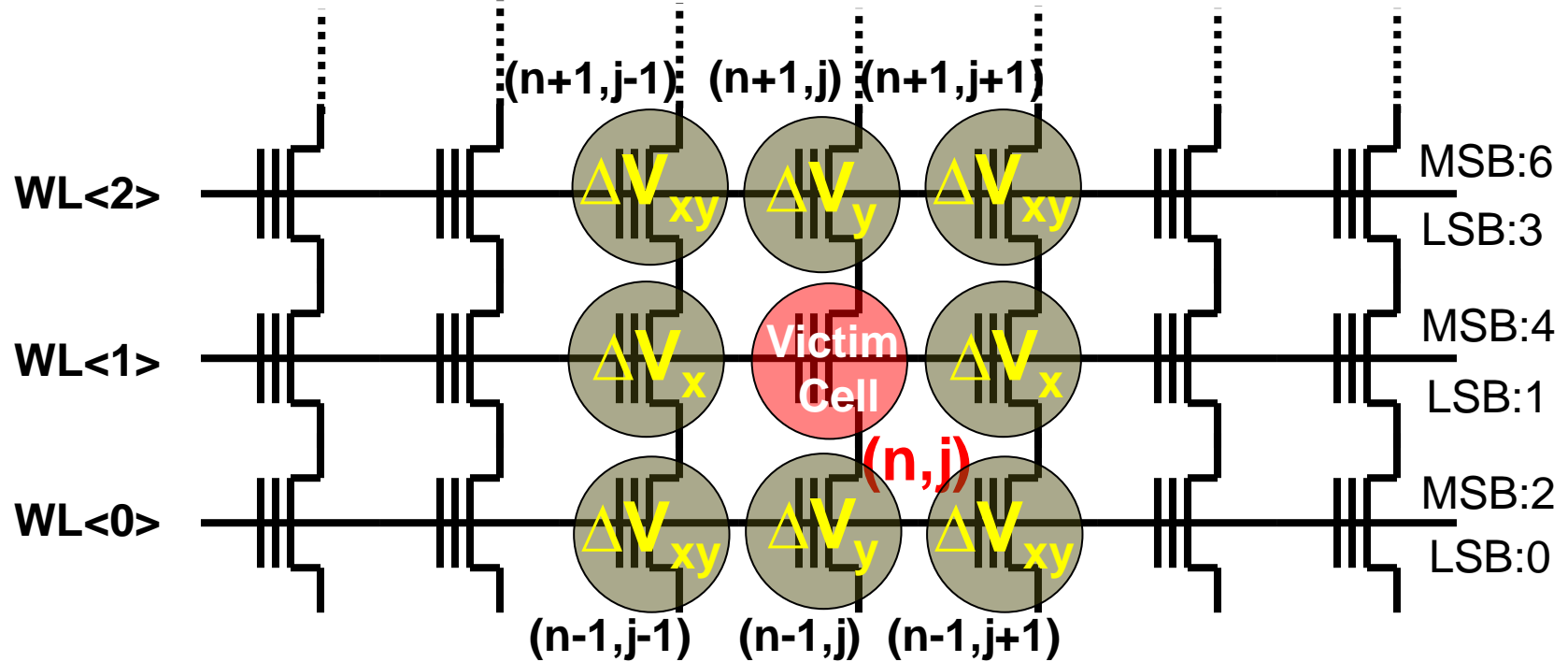
- When a cell is being programmed, **voltage level of a neighboring cell changes** (unintentionally) due to parasitic capacitance coupling  
→ **can change the data value stored**
- Also called program interference error
- Causes neighboring cell voltage to increase (shift right)
- Once retention errors are minimized, these errors can become dominant

# How Current Flash Cells are Programmed

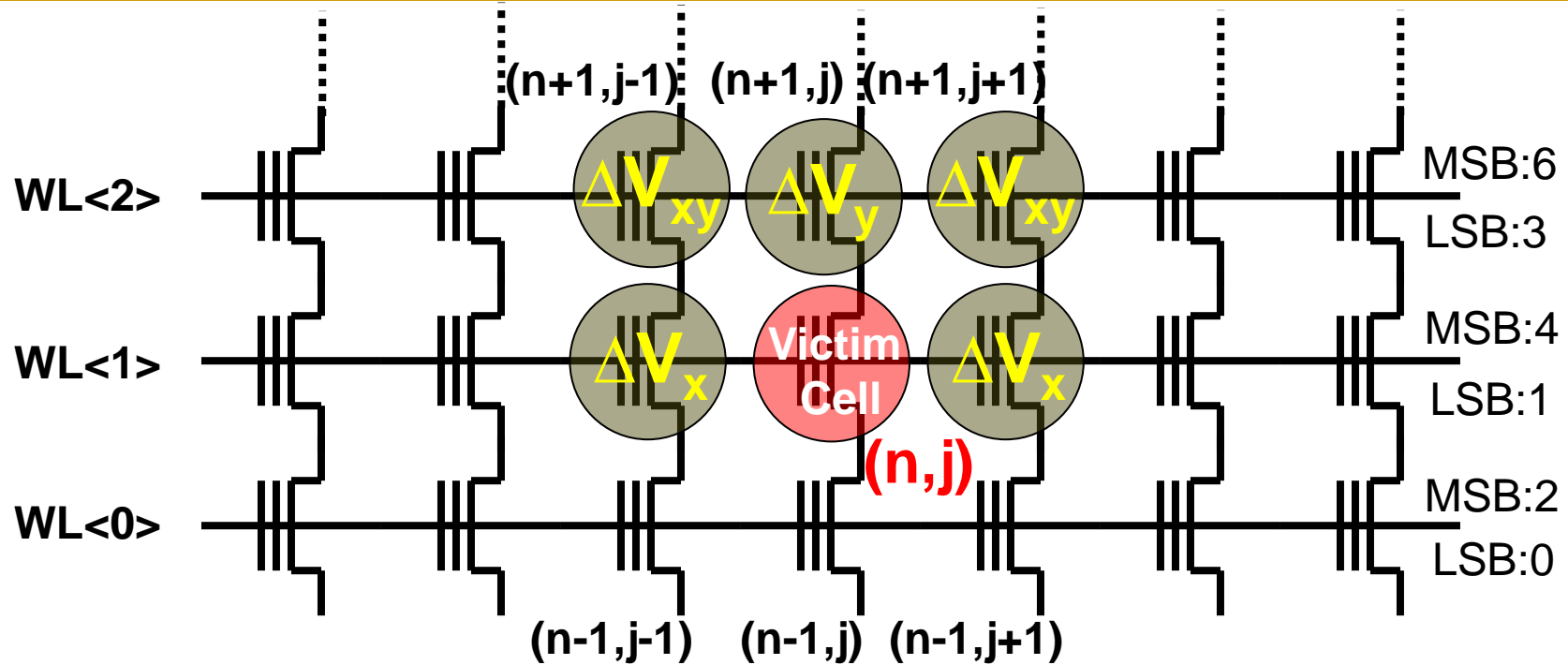
- Programming 2-bit MLC NAND flash memory in two steps



# Basics of Program Interference



# Traditional Model for $V_{th}$ Change



- Traditional model for victim cell threshold voltage change

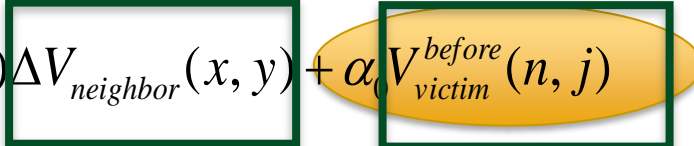
$$\Delta V_{victim} = (2C_x \Delta V_x + C_y \Delta V_y + 2C_{xy} \Delta V_{xy}) / C_{total}$$

**Not accurate and requires knowledge of coupling caps!**

# Our Goal and Idea

---

- Develop a new, more accurate and easier to implement model for program interference
- Idea:
  - Empirically characterize and model the effect of neighbor cell  $V_{th}$  changes on the  $V_{th}$  of the victim cell
  - Fit neighbor  $V_{th}$  change to a linear regression model and find the coefficients of the model via empirical measurement

$$\Delta V_{victim}(n, j) = \sum_{y=j-K}^{j+K} \sum_{x=n+1}^{n=M} \alpha(x, y) \Delta V_{neighbor}(x, y) + \alpha_0 V_{victim}^{before}(n, j)$$


Can be measured

# Developing a New Model via Empirical Measurement

---

- Feature extraction for  $V_{th}$  changes based on characterization
  - Threshold voltage changes on aggressor cell
  - Original state of victim cell
- Enhanced linear regression model

$$\Delta V_{victim}(n, j) = \sum_{y=j-K}^{j+K} \sum_{x=n+1}^{n=M} \alpha(x, y) \Delta V_{neighbor}(x, y) + \alpha_0 V_{victim}^{before}(n, j)$$

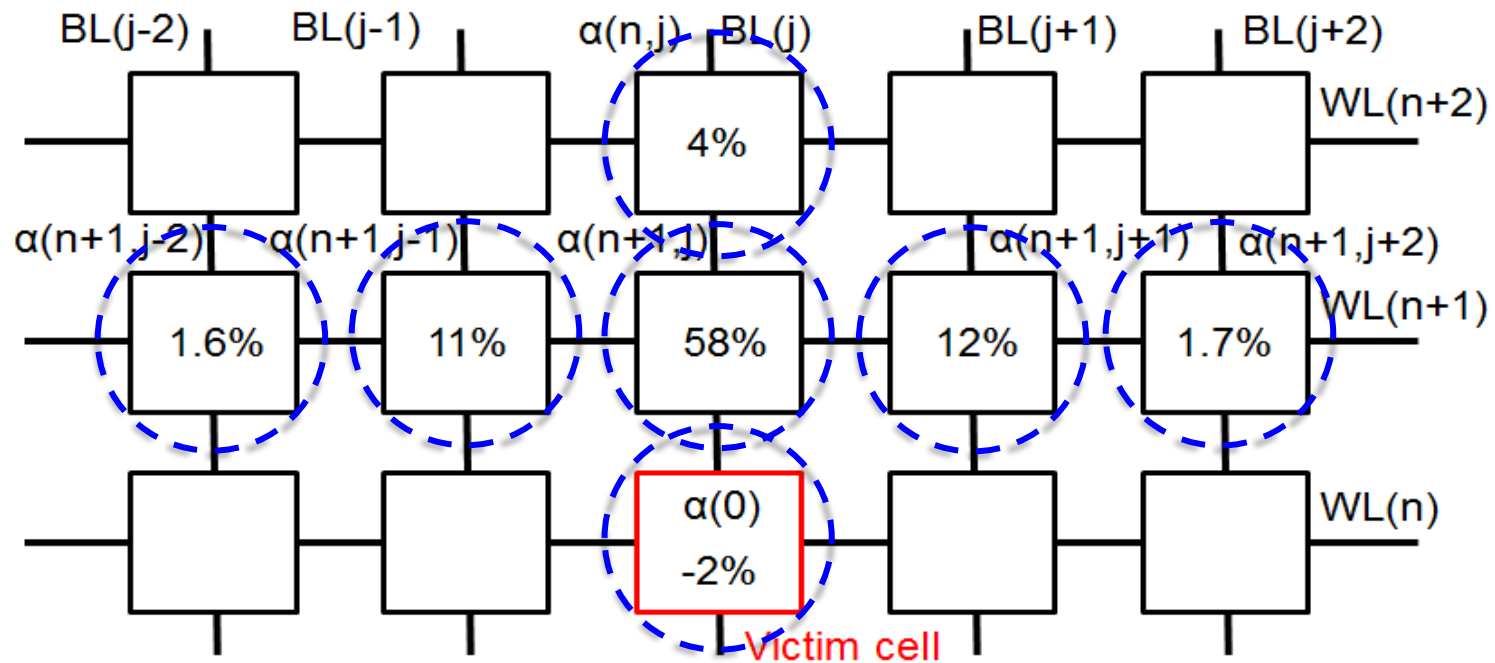
$$Y = X\alpha + \varepsilon \quad \longleftarrow \text{(vector expression)}$$

- Maximum likelihood estimation of the model coefficients

$$\arg \min_{\alpha} (\|X \times \alpha - Y\|_2^2 + \lambda \|\alpha\|_1)$$

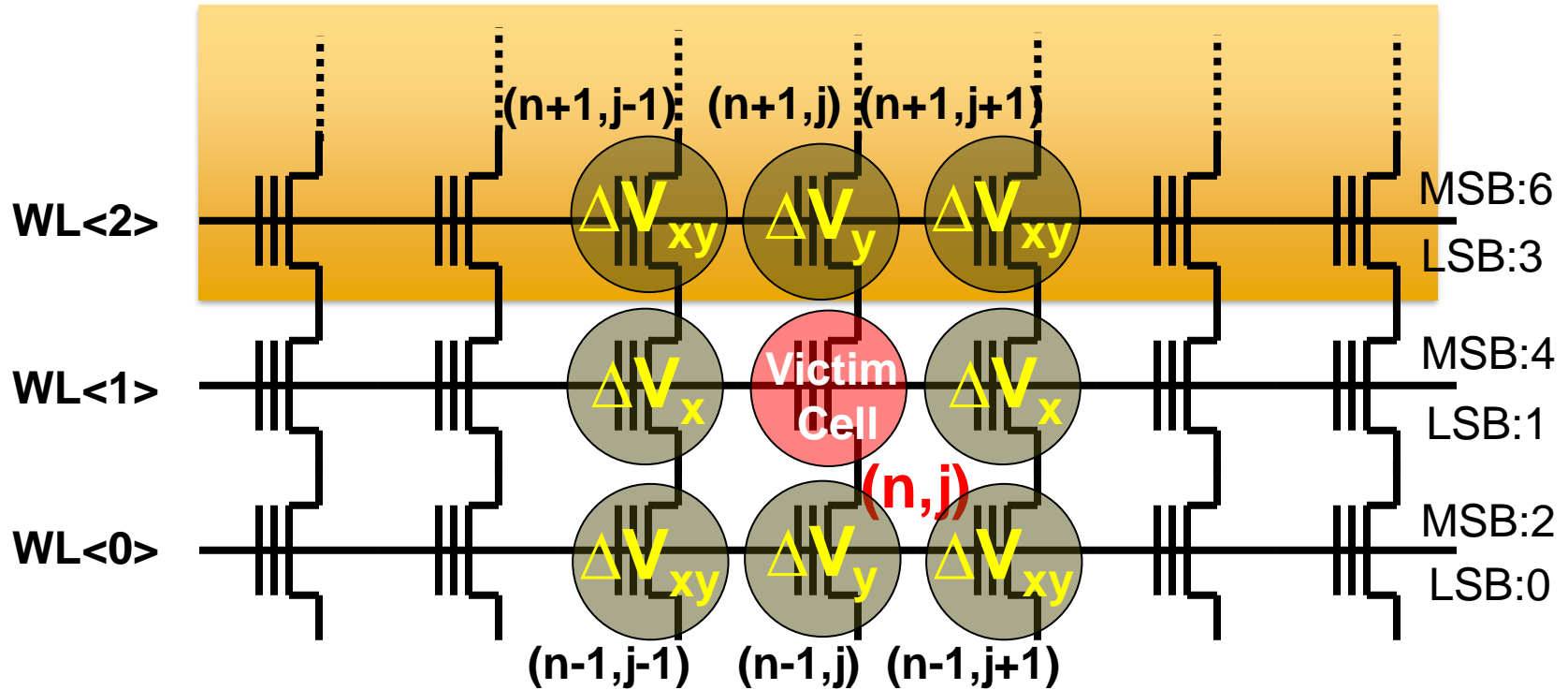


# Effect of Neighbor Voltages on the Victim



- Immediately-above cell interference is dominant
- Immediately-diagonal neighbor is the second dominant
- Far neighbor cell interference exists
- Victim cell's  $V_{th}$  has negative effect on interference

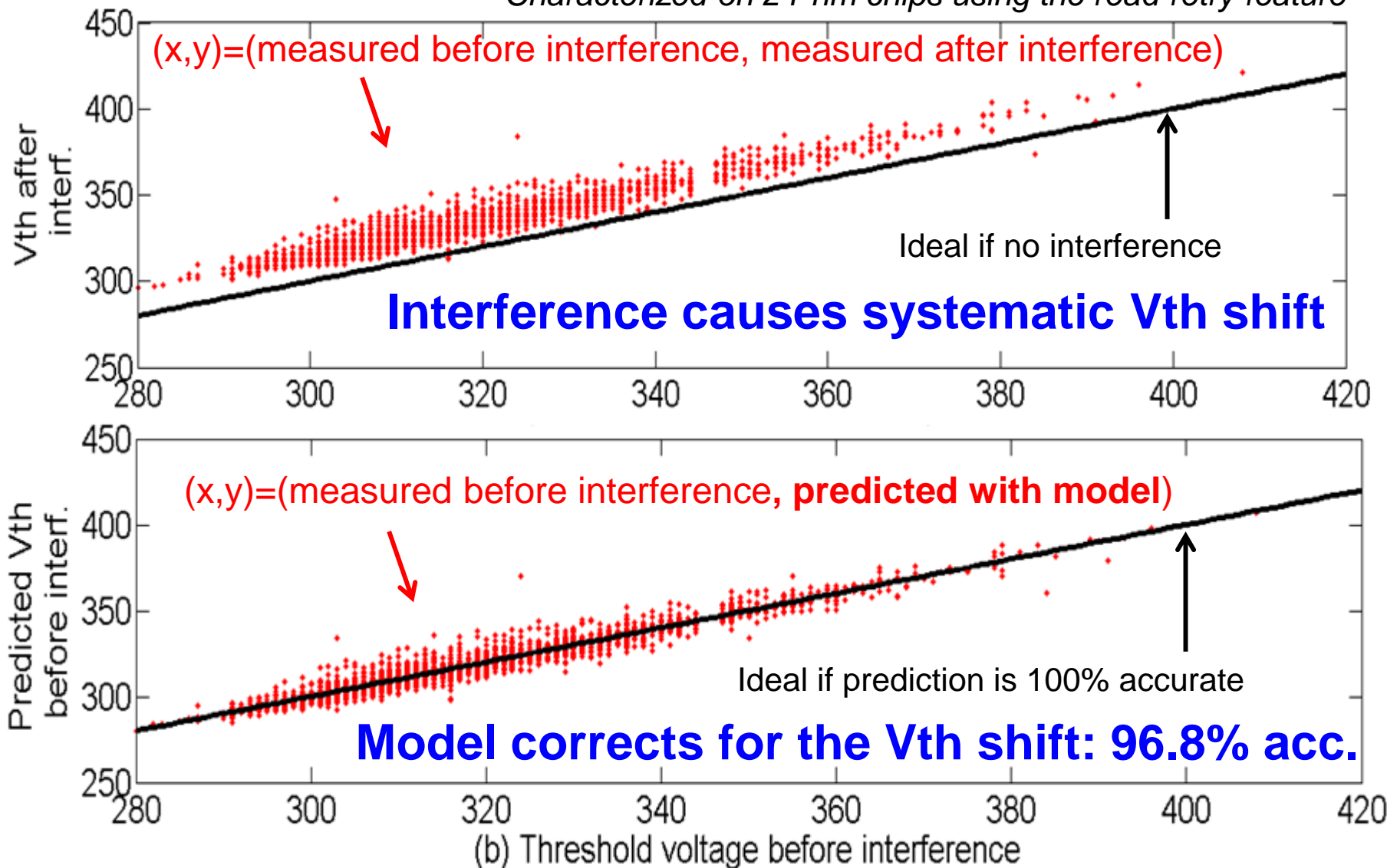
# New Model for Program Interference



$$\Delta V_{victim}(n, j) = \sum_{y=j-K}^{j+K} \sum_{x=n+1}^{n+M} \alpha(x, y) \Delta V_{neighbor}(x, y) + \alpha_0 V_{victim}^{before}(n, j)$$

# Model Accuracy

Characterized on 2Y-nm chips using the read-retry feature



# Many Other Results in the Paper

---

- Yu Cai, Onur Mutlu, Erich F. Haratsch, and Ken Mai,  
**"Program Interference in MLC NAND Flash Memory: Characterization, Modeling, and Mitigation"**  
*Proceedings of the 31st IEEE International Conference on Computer Design (ICCD)*, Asheville, NC, October 2013. [Slides \(pptx\)](#) [\(pdf\)](#) [Lightning Session Slides \(pdf\)](#)

## Program Interference in MLC NAND Flash Memory: Characterization, Modeling, and Mitigation

Yu Cai<sup>1</sup>, Onur Mutlu<sup>1</sup>, Erich F. Haratsch<sup>2</sup> and Ken Mai<sup>1</sup>

1. Data Storage Systems Center, Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA

2. LSI Corporation, San Jose, CA

yucaicai@gmail.com, {omutlu, kenmai}@andrew.cmu.edu

# Agenda

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- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Main Characterization Results
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  - Read Disturb Error Handling
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  - 3D NAND Flash Memory Reliability
- Summary

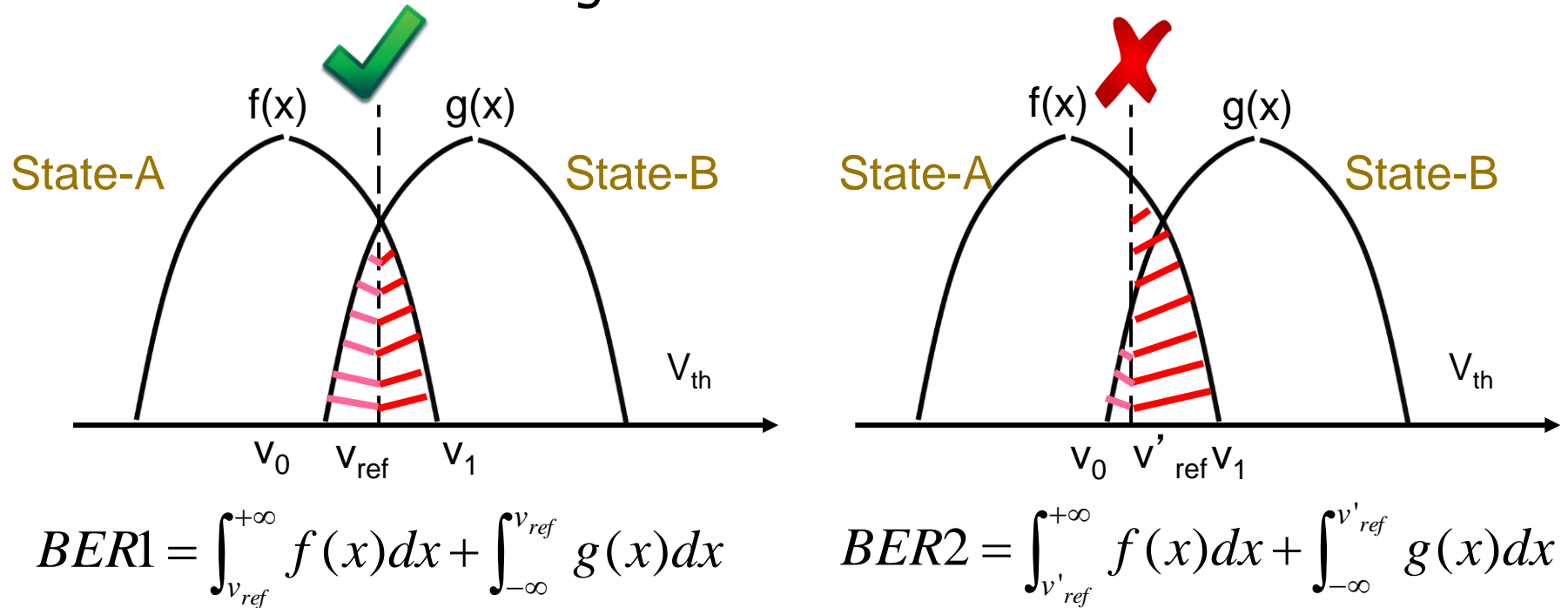
# Mitigation: Applying the Model

---

- So, what can we do with the model?
- Goal: Mitigate the effects of program interference caused voltage shifts

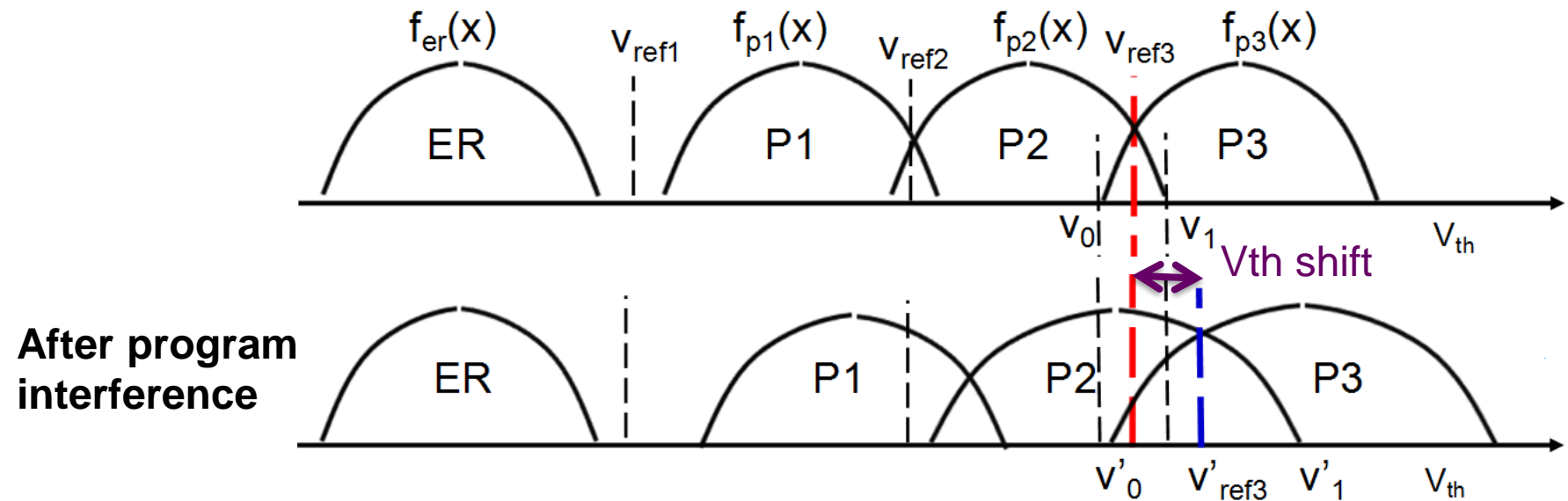
# Optimum Read Reference for Flash Memory

- Read reference voltage affects the raw bit error rate



- There exists an optimal read reference voltage
  - Predictable if the statistics (i.e. mean, variance) of threshold voltage distributions are characterized and modeled

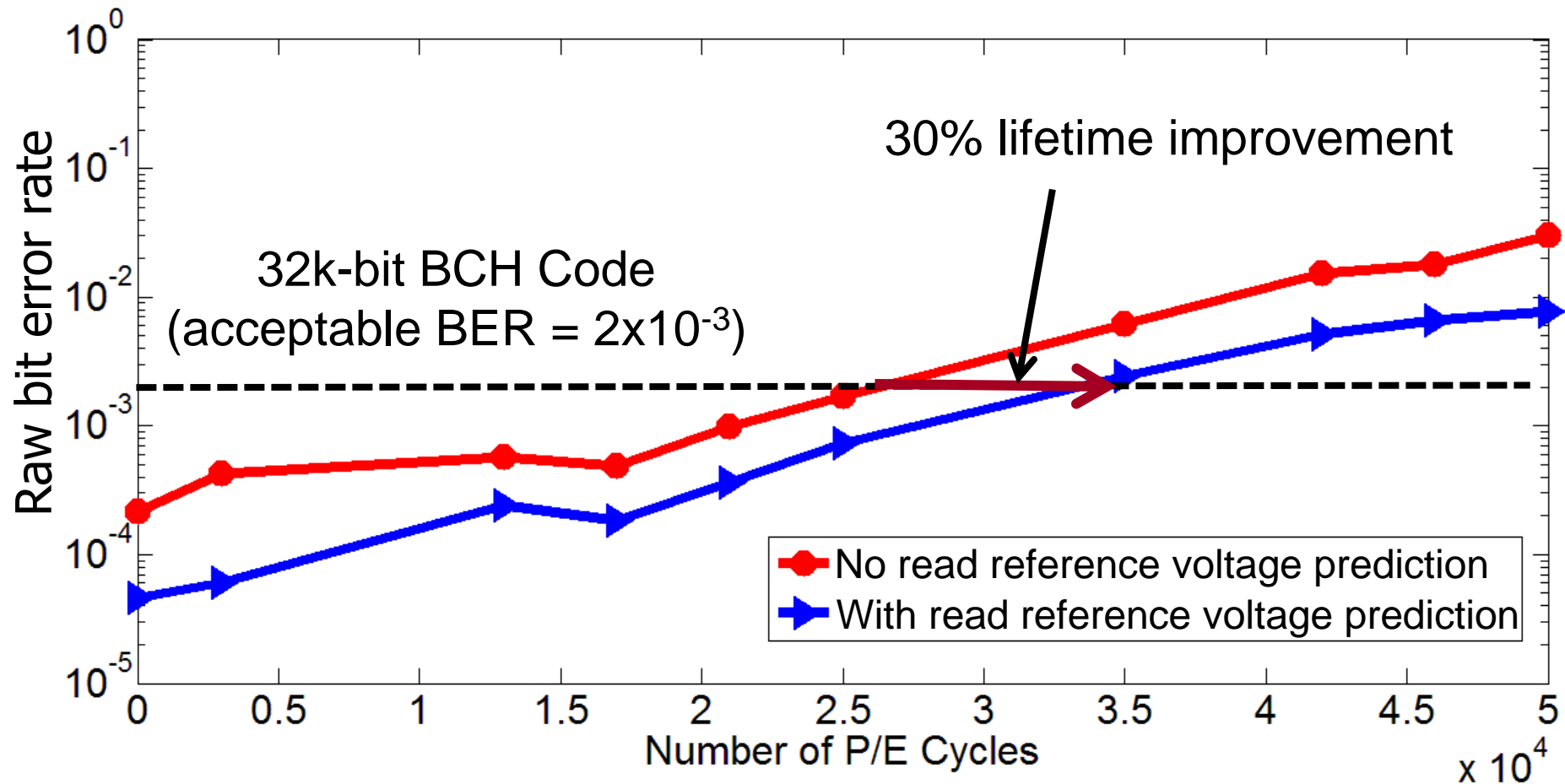
# Optimum Read Reference Voltage Prediction



- Vth shift learning (done every  $\sim 1k$  P/E cycles)
  - Program sample cells with known data pattern and test  $V_{th}$
  - Program aggressor neighbor cells and test victim  $V_{th}$  after interference
  - Characterize the mean shift in  $V_{th}$  (i.e., program interference noise)
- Optimum read reference voltage prediction
  - Default read reference voltage + Predicted mean  $V_{th}$  shift by model



# Effect of Read Reference Voltage Prediction



- Read reference voltage prediction reduces raw BER (by 64%) and increases the P/E cycle lifetime (by 30%)

# More on Read Reference Voltage Prediction

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Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, Onur Mutlu

# Readings on Flash Memory



*Proceedings of the IEEE, Sept. 2017*



## Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

*This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.*

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*Invited Book Chapter in Inside Solid State Drives, 2018.*  
[Preliminary arxiv.org version]

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# Flash Memory Reliability

# Agenda

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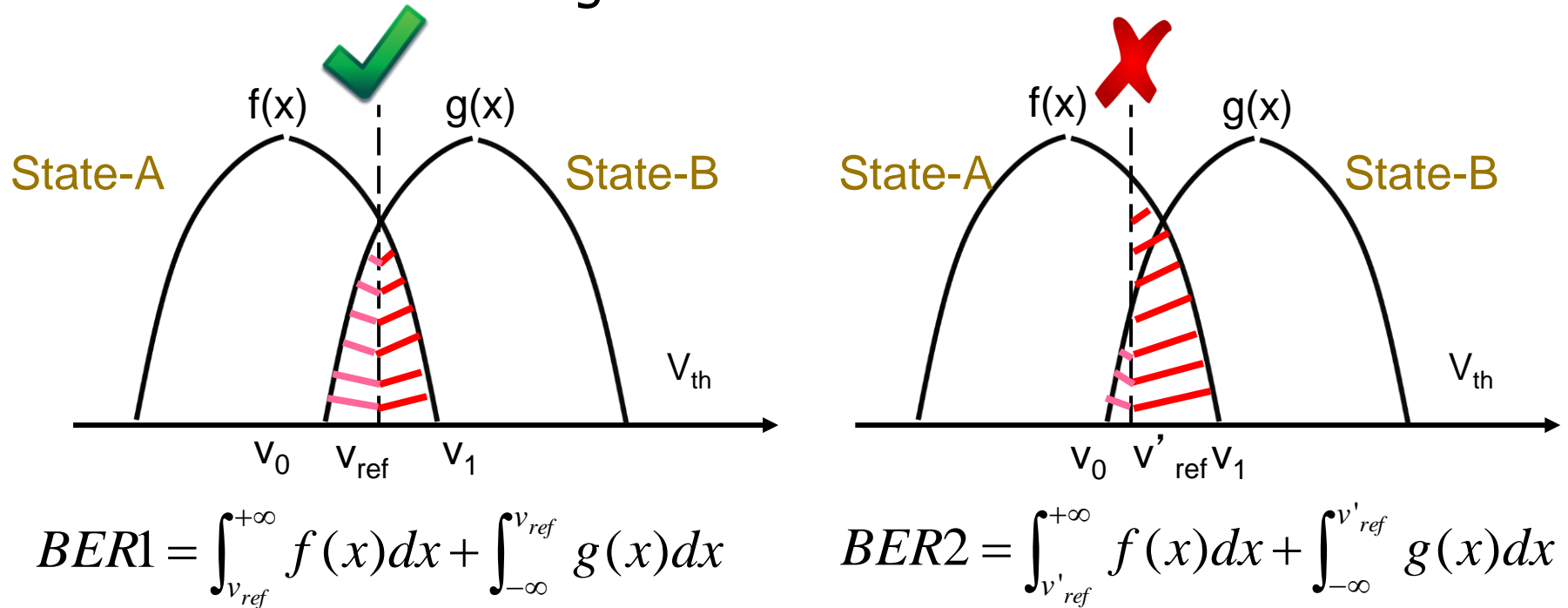
# Using the Vth Distribution Models

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- So, what can we do with the model?
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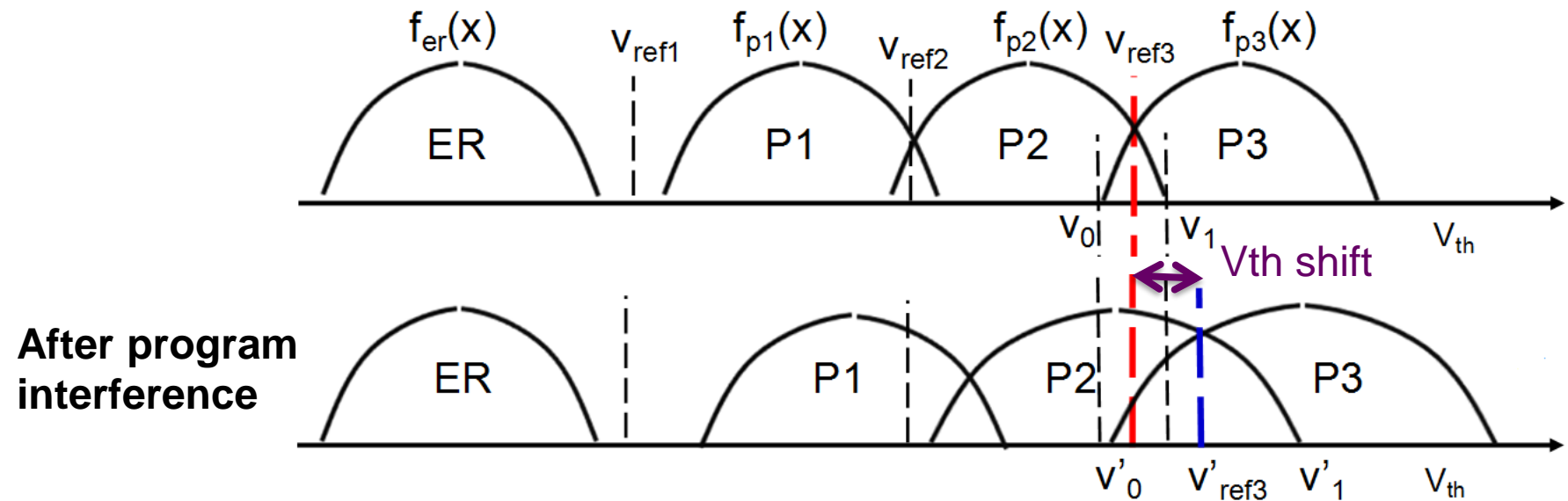
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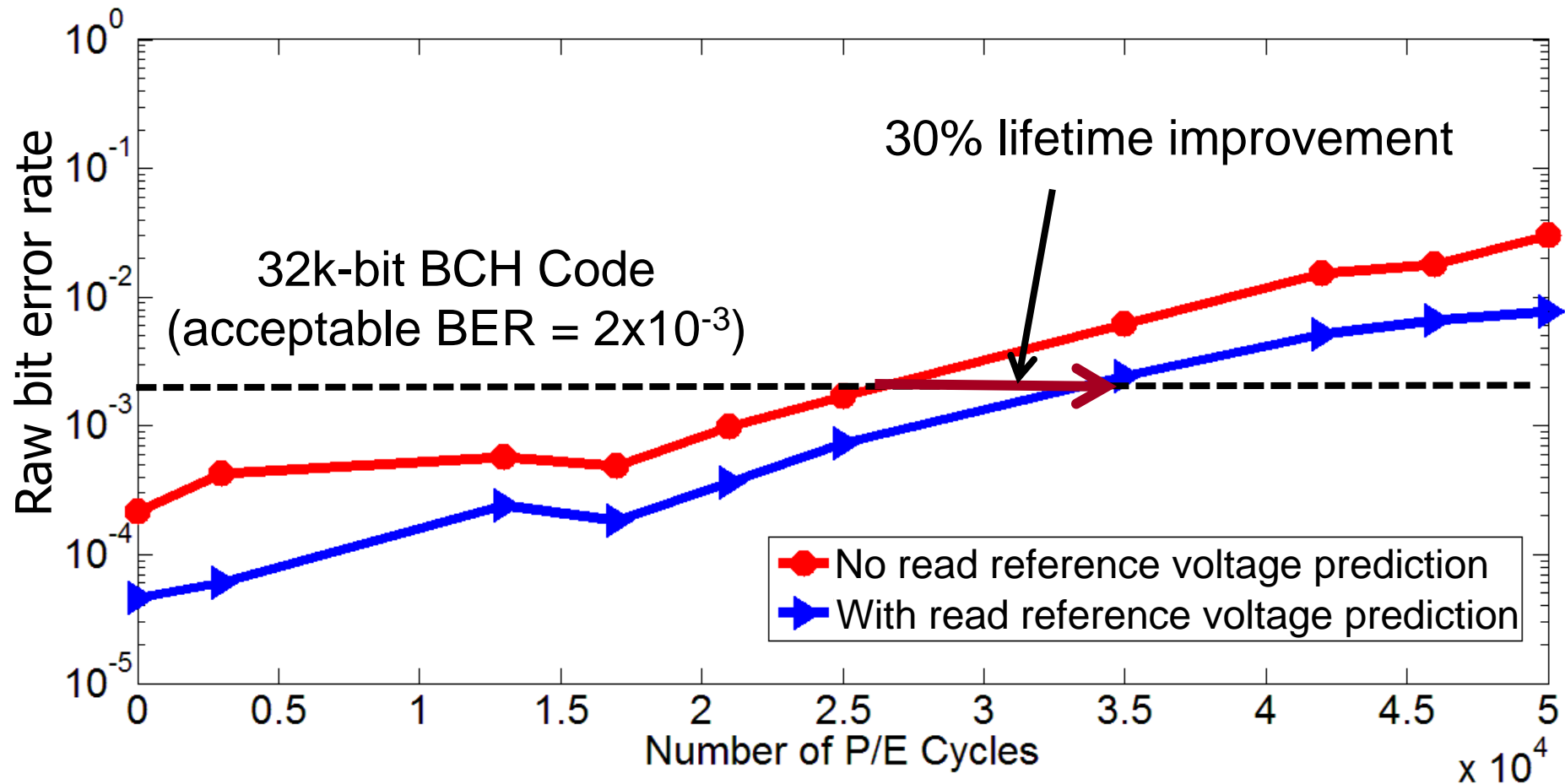
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# More Accurate and Online Channel Modeling

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## Enabling Accurate and Practical Online Flash Channel Modeling for Modern MLC NAND Flash Memory

Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, Onur Mutlu

# Non-Gaussian $V_{th}$ Distributions (1X-nm)

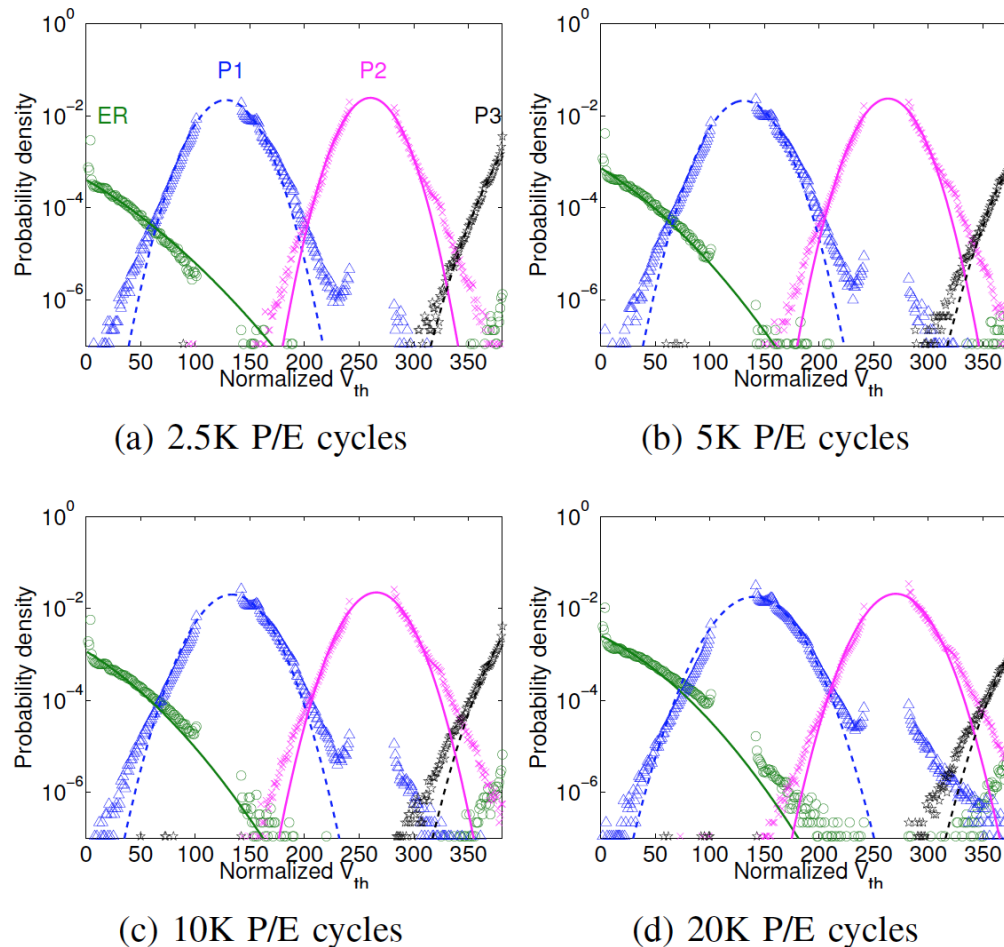


Fig. 4: Gaussian-based model (solid/dashed lines) vs. data measured from real NAND flash chips (markers) under different P/E cycle counts.

# Better Modeling of $V_{th}$ Distributions (I)

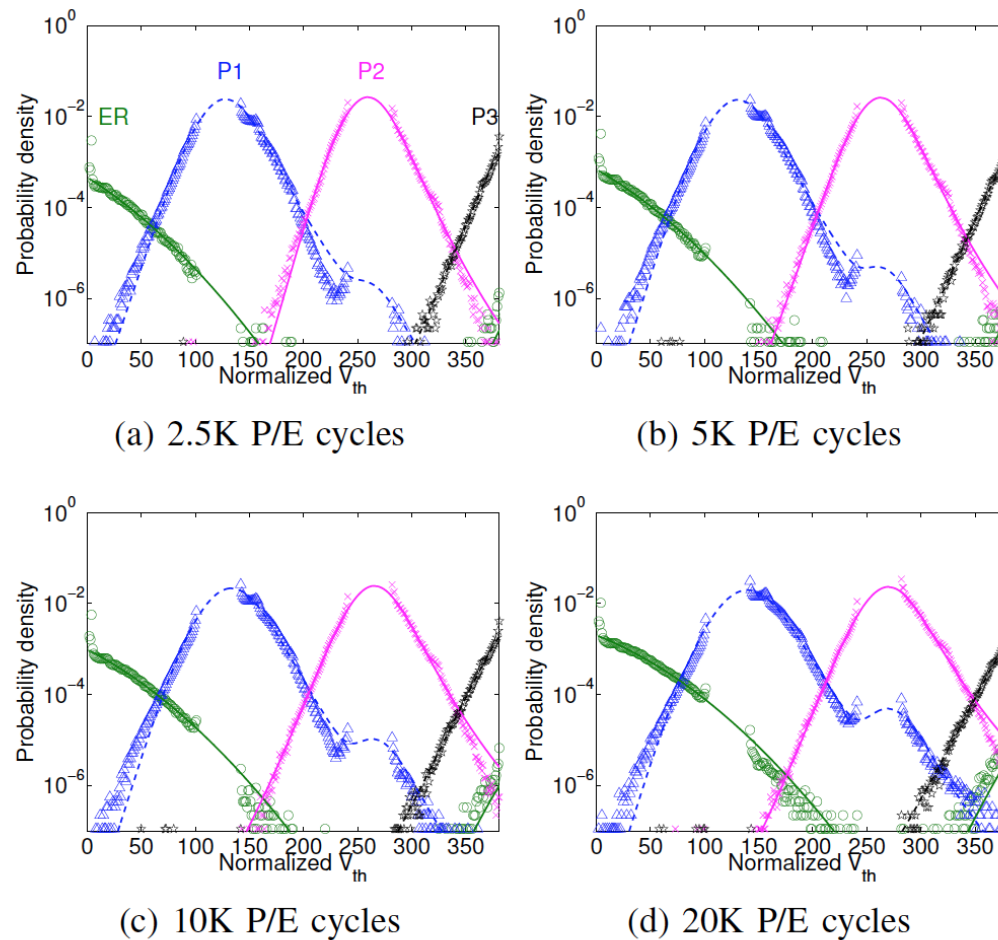


Fig. 6: Our new Student's t-based model (solid/dashed lines) vs. data measured from real NAND flash chips (markers) under different P/E cycle counts.



# Better Modeling of Vth Distributions (II)

P/E Cycles	0	2.5K	5K	7.5K	10K	12K	14K	16K	18K	20K	AVG
<b>Gaussian</b>	.99%	1.8%	1.6%	1.8%	1.9%	2.4%	3.1%	8.7%	2.1%	2.3%	<b>2.6%</b>
<b>Normal-Laplace</b>	.34%	.46%	.55%	.61%	.63%	.67%	.68%	.70%	.67%	.67%	<b>.61%</b>
<b>Student's t</b>	.37%	.51%	.61%	.68%	.70%	.76%	.76%	.78%	.76%	.78%	<b>.68%</b>

TABLE 1: Modeling error of the evaluated threshold voltage distribution models, at various P/E cycle counts.

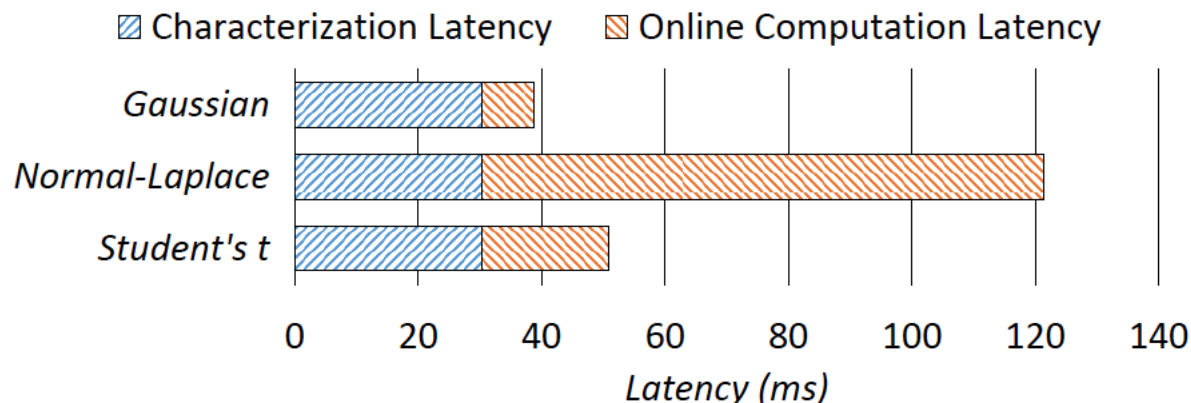


Fig. 8: Overall latency breakdown of the three evaluated threshold voltage distribution models for static modeling.

# V<sub>th</sub> Prediction vs. Reality with Better Modeling

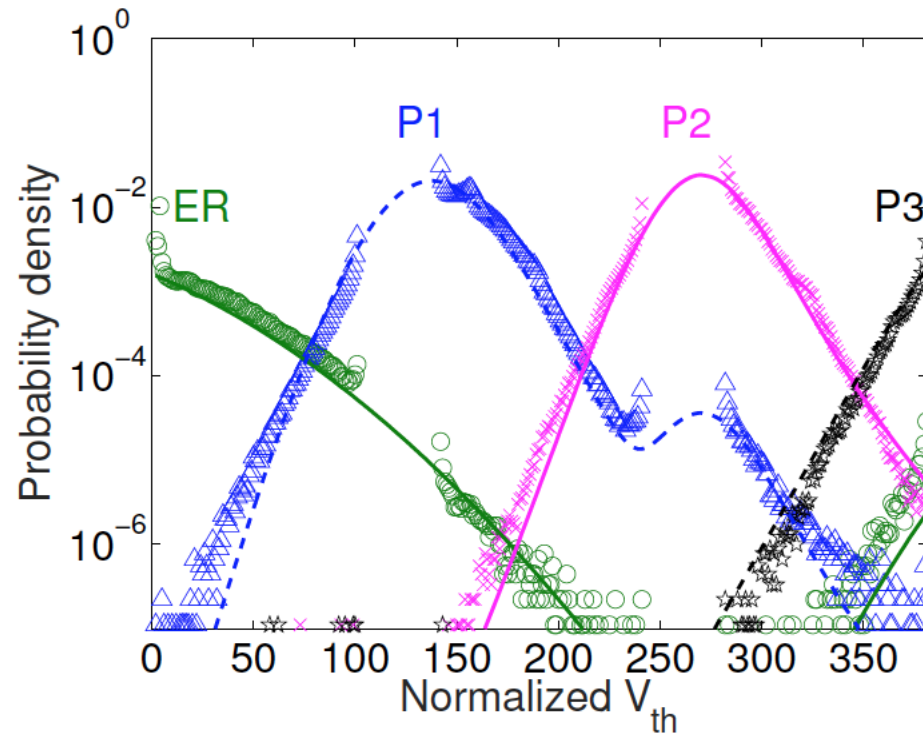


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# Online Read Reference Voltage Prediction

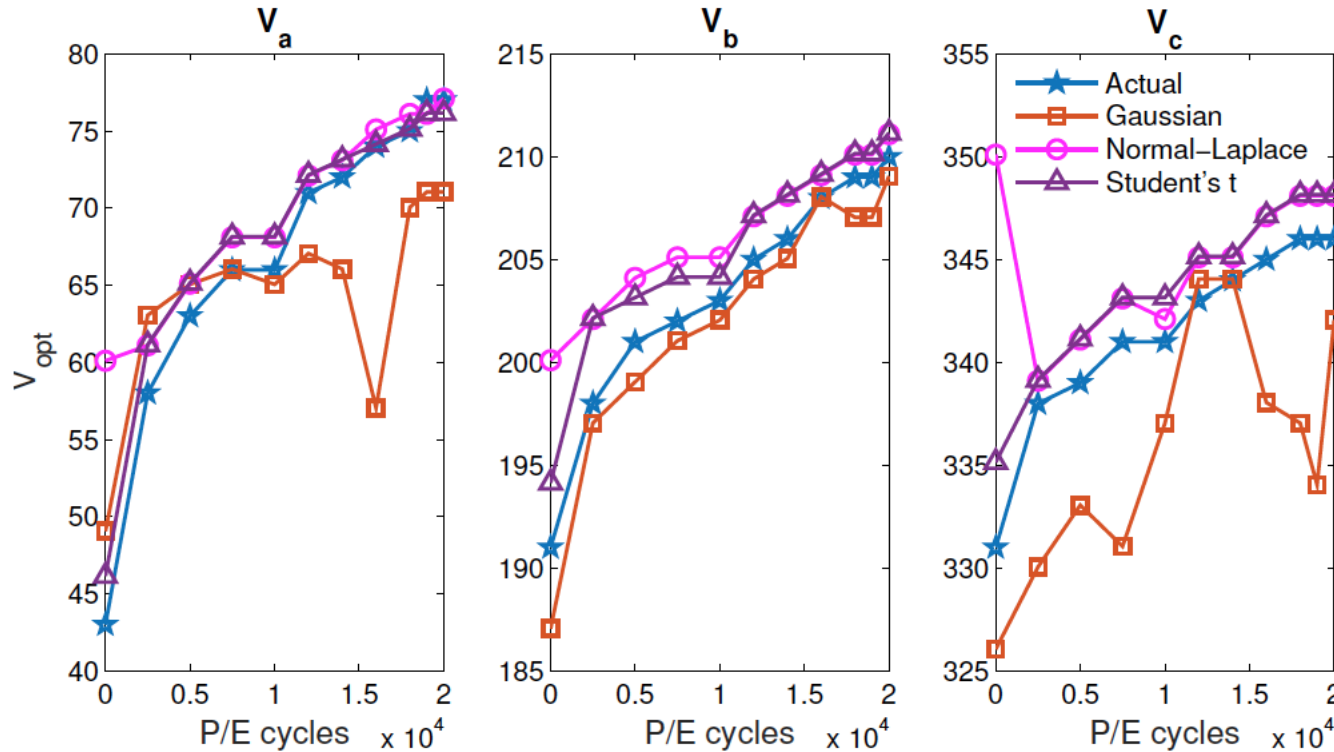


Fig. 16: Actual and modeled *optimal* read reference voltages ( $V_{opt}$ ) using the three evaluated threshold voltage distribution models at different P/E cycle counts.

# Effect on RBER of Read Ref V Prediction

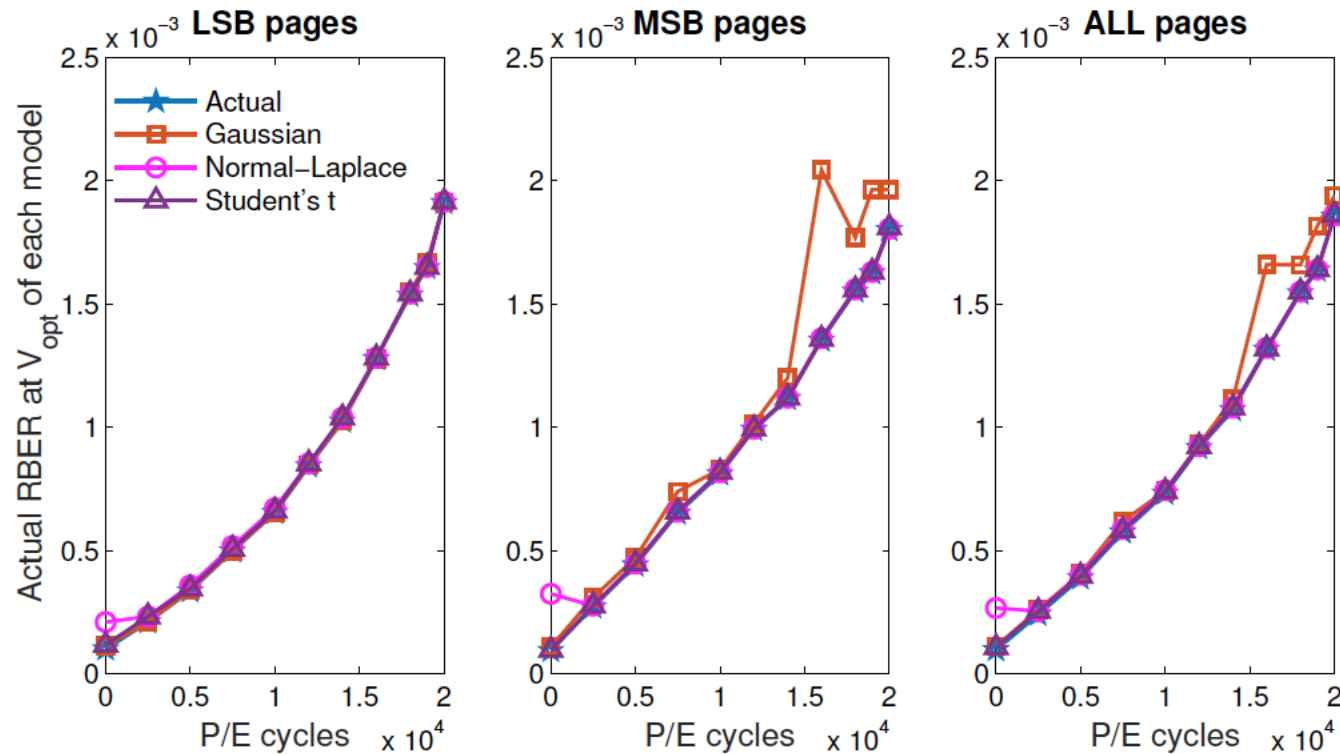


Fig. 17: RBER achieved by actual and modeled *optimal* read reference voltages ( $V_{opt}$ ) using the three evaluated threshold voltage distribution models at different P/E cycle counts.

# More Accurate and Online Channel Modeling

---

- Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, and Onur Mutlu,  
**"Enabling Accurate and Practical Online Flash Channel Modeling  
for Modern MLC NAND Flash Memory"**  
*to appear in IEEE Journal on Selected Areas in Communications (JSAC),  
2016.*

## Enabling Accurate and Practical Online Flash Channel Modeling for Modern MLC NAND Flash Memory

Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, Onur Mutlu

# Agenda

---

- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Main Characterization Results
  - Retention-Aware Error Management
  - Threshold Voltage and Program Interference Analysis
  - Read Reference Voltage Prediction
  - Neighbor-Assisted Error Correction
  - Read Disturb Error Handling
  - Retention Error Handling
  - 3D NAND Flash Memory Reliability
- Summary

# Goal

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- Develop a better error correction mechanism for cases where ECC fails to correct a page

# Observations So Far

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- Immediate neighbor cell has the most effect on the victim cell when programmed
- A single set of read reference voltages is used to determine the value of the (victim) cell
- The set of read reference voltages is determined based on the ***overall threshold voltage distribution of all cells*** in flash memory



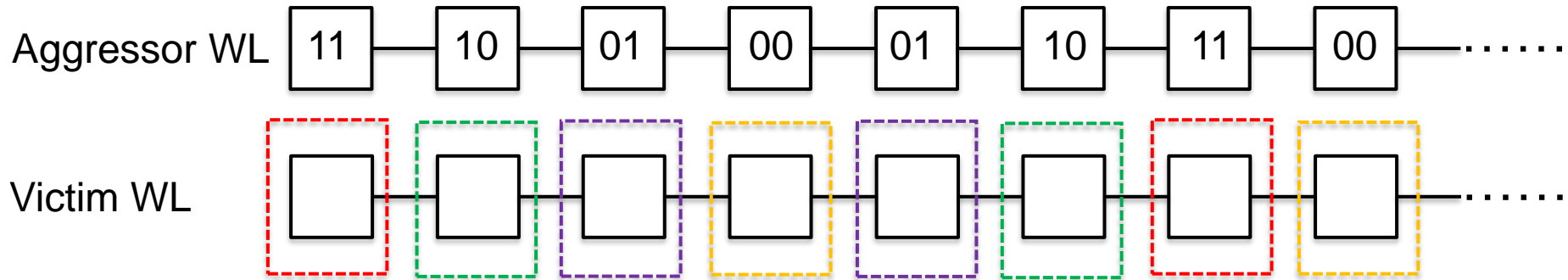
# New Observations [Cai+ SIGMETRICS'14]

---

- Vth distributions of **cells with different-valued immediate-neighbor cells** are significantly different
  - Because neighbor value affects the amount of Vth shift
- **Corollary:** If we know the value of the immediate-neighbor, we can find a **more accurate set of read reference voltages** based on the “conditional” threshold voltage distribution

Cai et al., **Neighbor-Cell Assisted Error Correction for MLC NAND Flash Memories**, SIGMETRICS 2014.

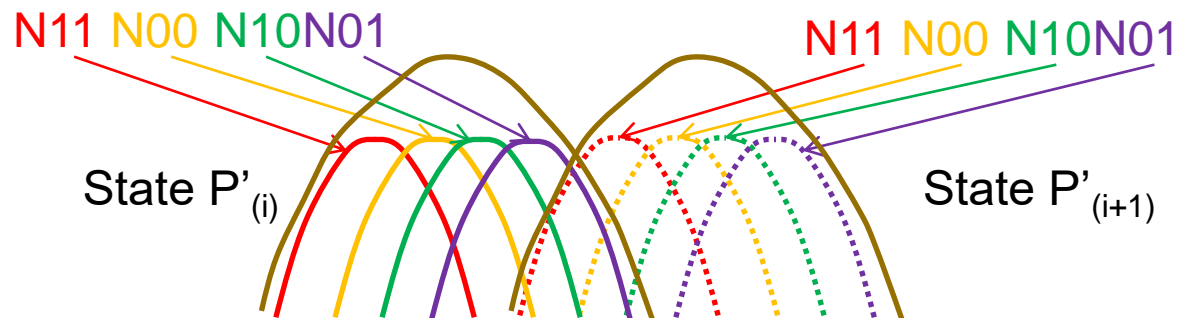
# Secrets of Threshold Voltage Distributions



Victim WL **before** MSB  
page of aggressor WL  
are programmed



Victim WL **after** MSB  
page of aggressor WL  
are programmed

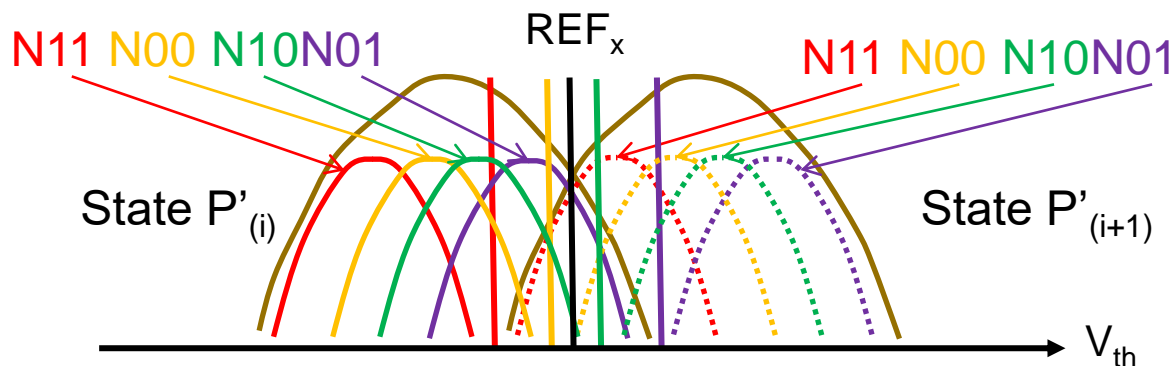


# If We Knew the Immediate Neighbor ...

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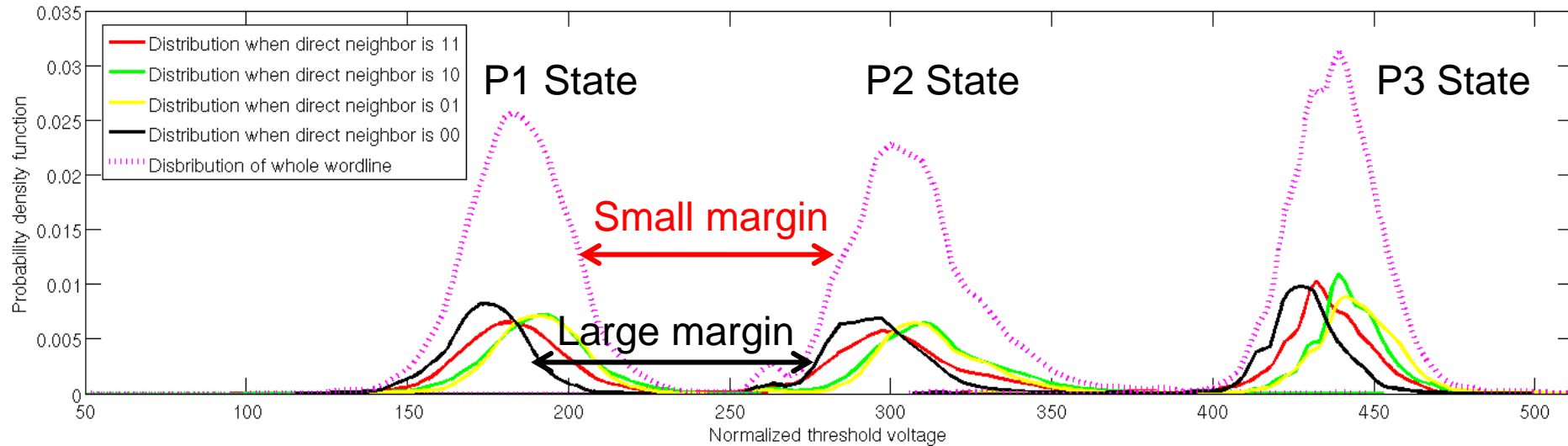
- Then, we could choose a different read reference voltage to more accurately read the “victim” cell

# Overall vs Conditional Reading



- Using the optimum read reference voltage based on the overall distribution leads to more errors
- Better to use the optimum read reference voltage based on the conditional distribution (i.e., value of the neighbor)
  - Conditional distributions of two states are farther apart from each other

# Real NAND Flash Chip Measurement Results



	Overall	$x_{11}$ (ER)	$x_{10}$ (P1)	$x_{00}$ (P2)	$x_{01}$ (P3)
Distance	65.4	65.4	64.7	66.4	65.8
Variance	385.9	286.2	256.7	242.8	252.1
SNR	3.4	3.8	3.9	4.2	4.1
BER	$3 \times 10^{-4}$	$7 \times 10^{-5}$	$5 \times 10^{-5}$	$2 \times 10^{-5}$	$3 \times 10^{-5}$

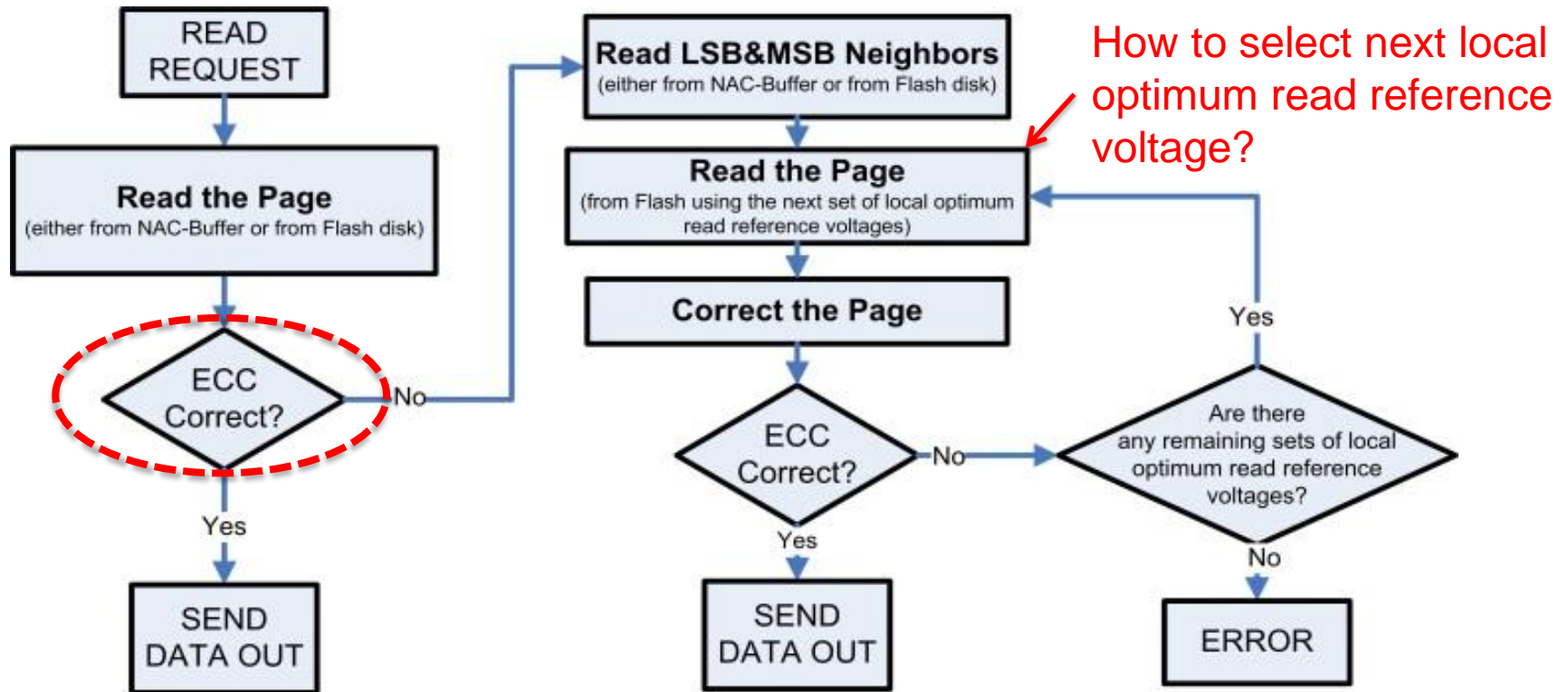
**Raw BER of conditional reading is much smaller than overall reading**

# Idea: Neighbor Assisted Correction (NAC)

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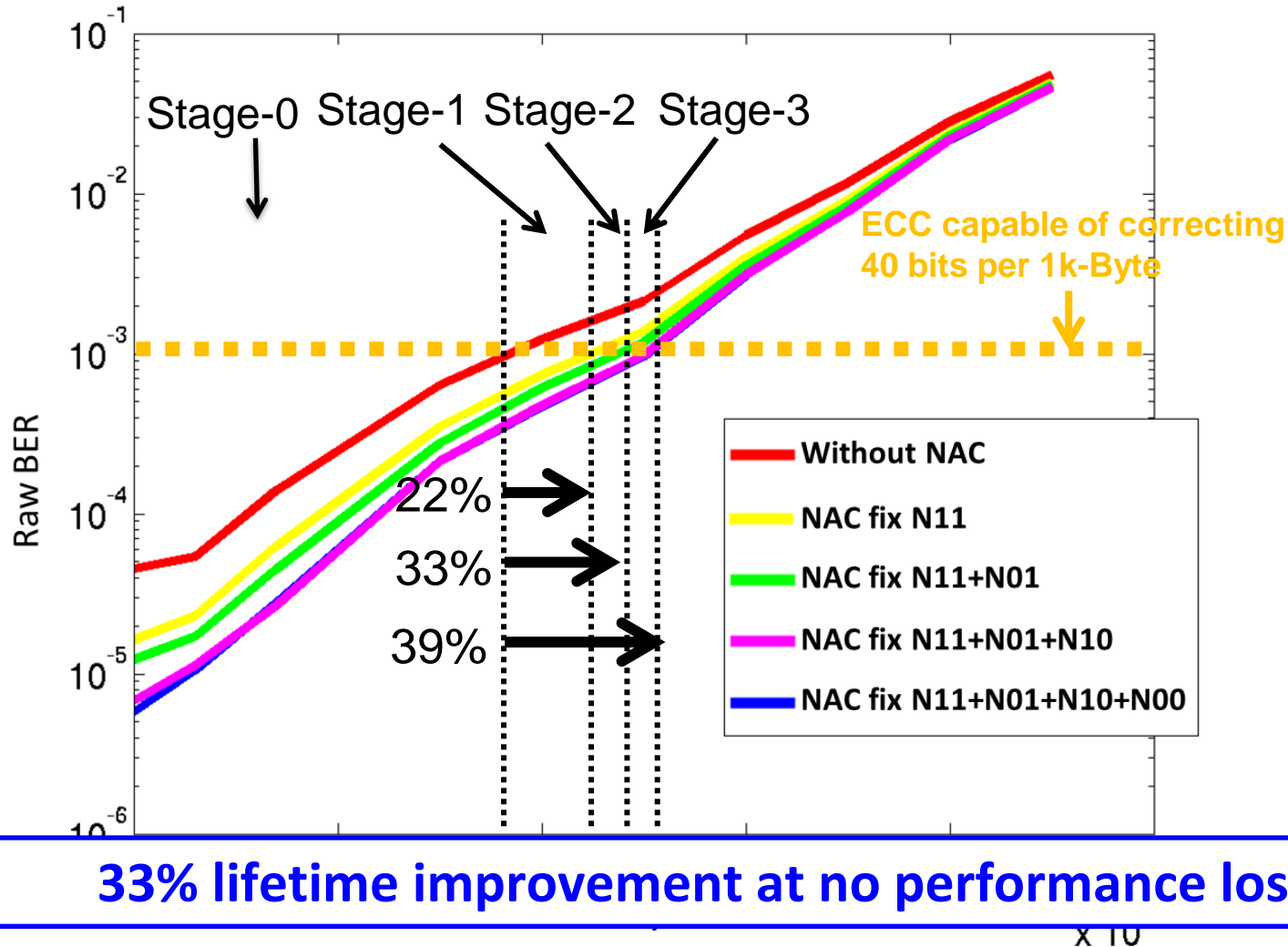
- Read a page with the read reference voltages based on overall  $V_{th}$  distribution (same as today) and buffer it
- If ECC fails:
  - Read the immediate-neighbor page
  - Re-read the page using the read reference voltages corresponding to the voltage distribution assuming a particular immediate-neighbor value
  - Replace the buffered values of the cells with that particular immediate-neighbor cell value
  - Apply ECC again

# Neighbor Assisted Correction Flow



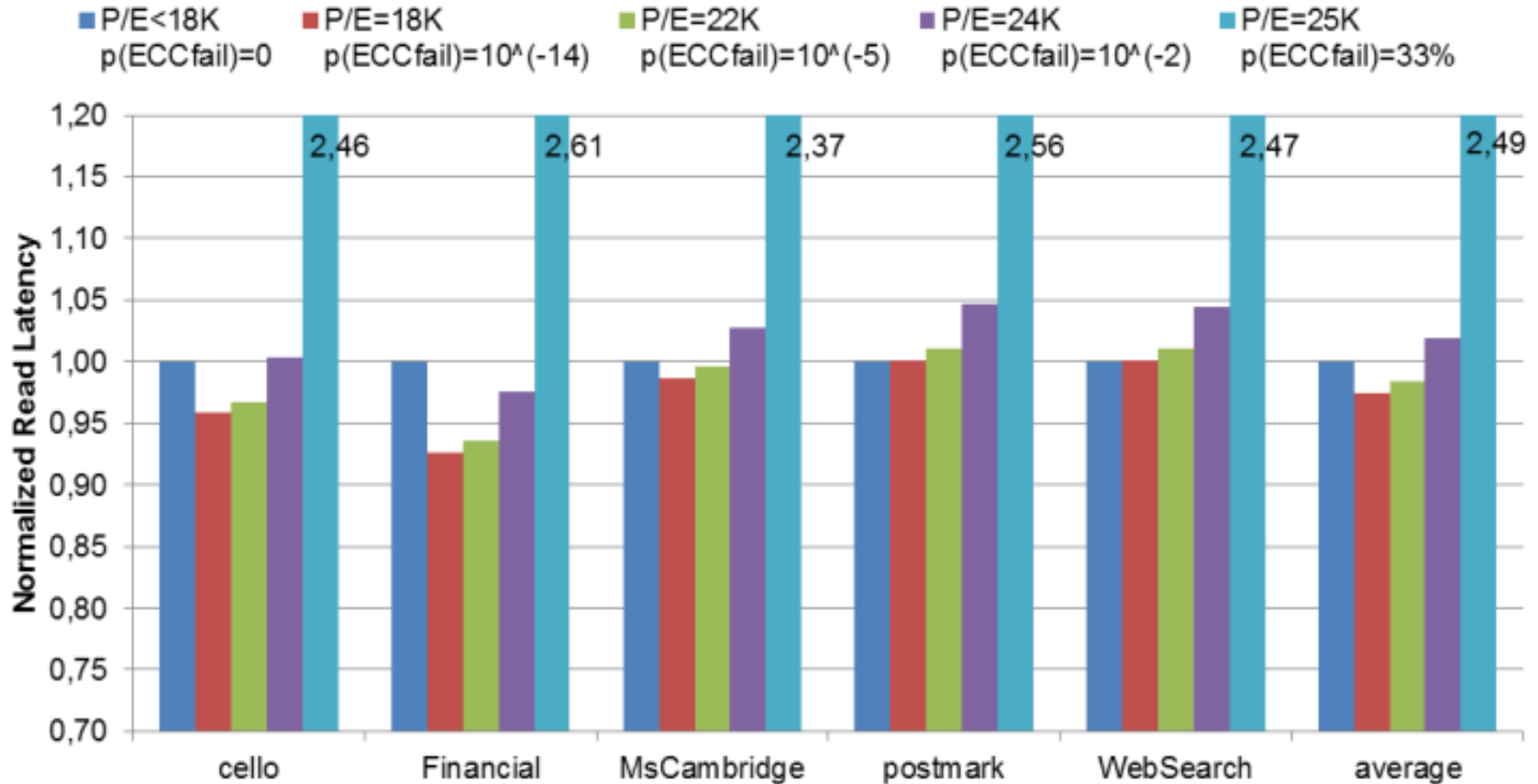
- Trigger neighbor-assisted reading only when ECC fails
- Read neighbor values and use corresponding read reference voltages in a prioritized order until ECC passes

# Lifetime Extension with NAC





# Performance Analysis of NAC



No performance loss within nominal lifetime  
and with reasonable (1%) ECC fail rates

# More on Neighbor-Assisted Correction

---

- Yu Cai, Gulay Yalcin, Onur Mutlu, Eric Haratsch, Osman Unsal, Adrian Cristal, and Ken Mai,  
**"Neighbor-Cell Assisted Error Correction for MLC NAND Flash Memories"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (**SIGMETRICS**), Austin, TX, June 2014. [Slides \(ppt\)](#) [\(pdf\)](#)*

## Neighbor-Cell Assisted Error Correction for MLC NAND Flash Memories

Yu Cai<sup>1</sup>, Gulay Yalcin<sup>2</sup>, Onur Mutlu<sup>1</sup>, Erich F. Haratsch<sup>4</sup>,  
Osman Unsal<sup>2</sup>, Adrian Cristal<sup>2,3</sup>, and Ken Mai<sup>1</sup>

<sup>1</sup>Electrical and Computer Engineering Department, Carnegie Mellon University

<sup>2</sup>Barcelona Supercomputing Center, Spain

<sup>3</sup>IIIA – CSIC – Spain National Research Council

<sup>4</sup>LSI Corporation

yucaicai@gmail.com, {omutlu, kenmai}@ece.cmu.edu, {gulay.yalcin, adrian.cristal, osman.unsal}@bsc.es

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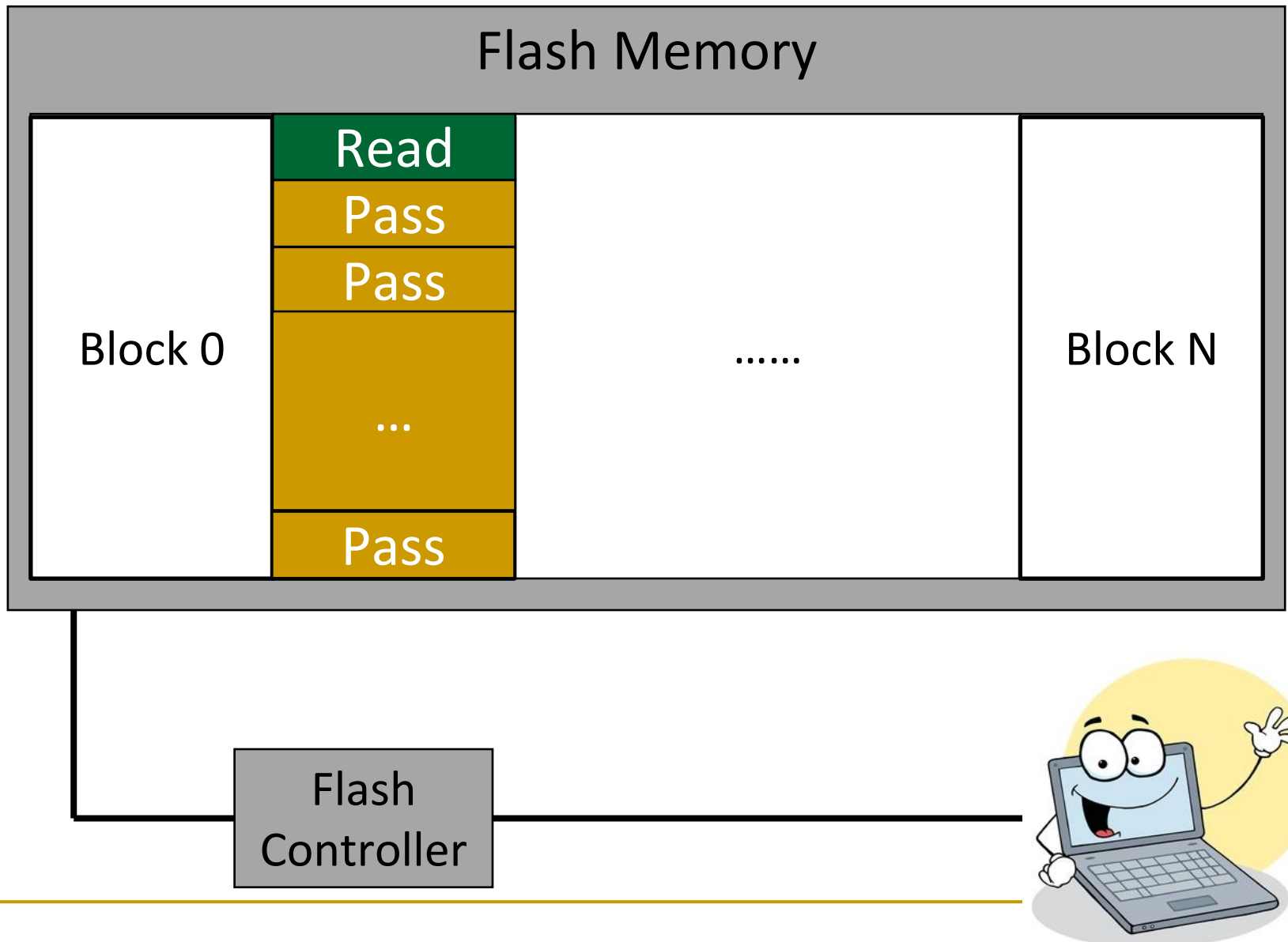
# Read Disturb Errors in Flash Memory

# One Issue: Read Disturb in Flash Memory

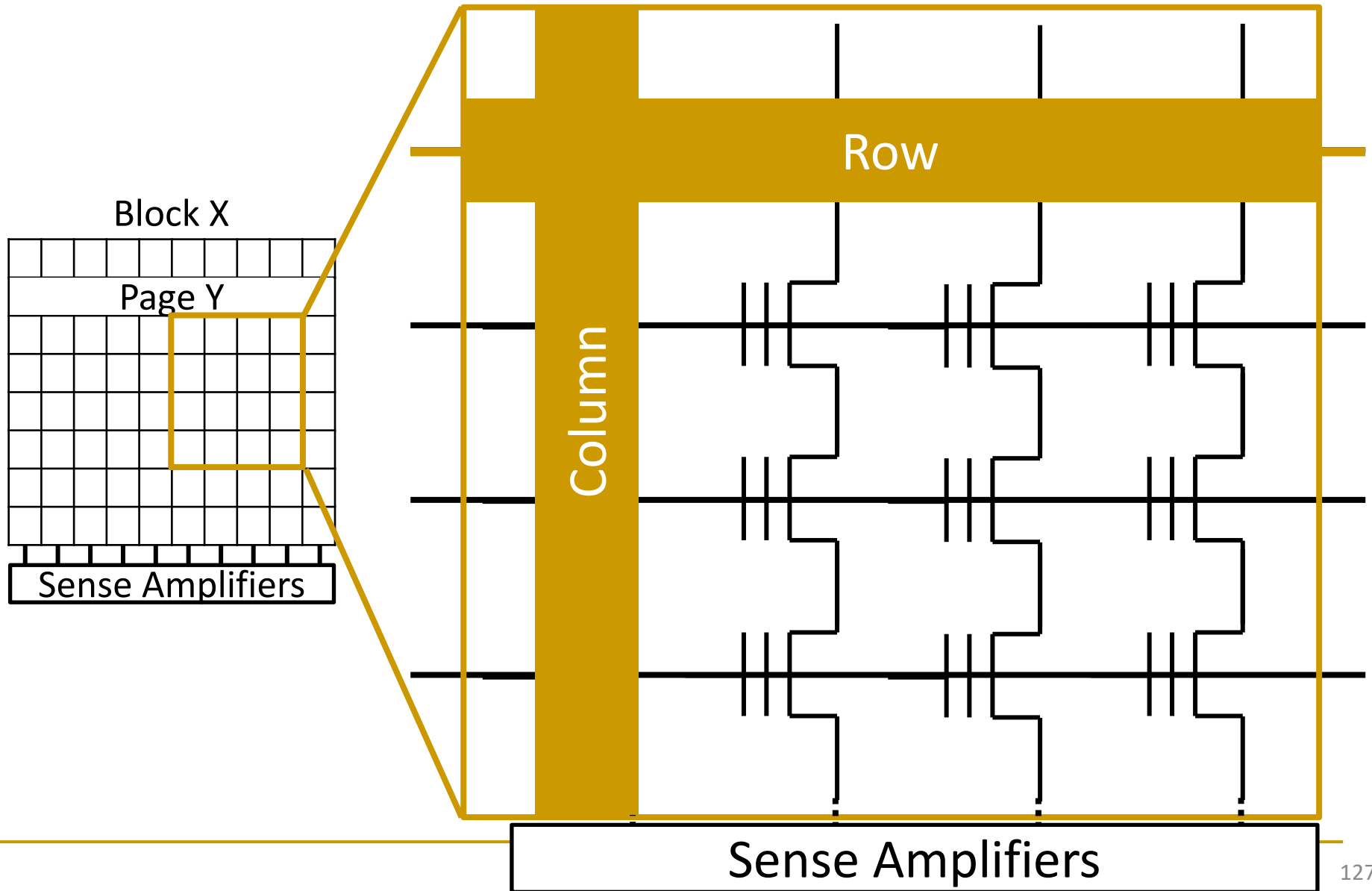
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- All scaled memories are prone to read disturb errors
- DRAM
- SRAM
- Hard Disks: Adjacent Track Interference
- NAND Flash

# NAND Flash Memory Background

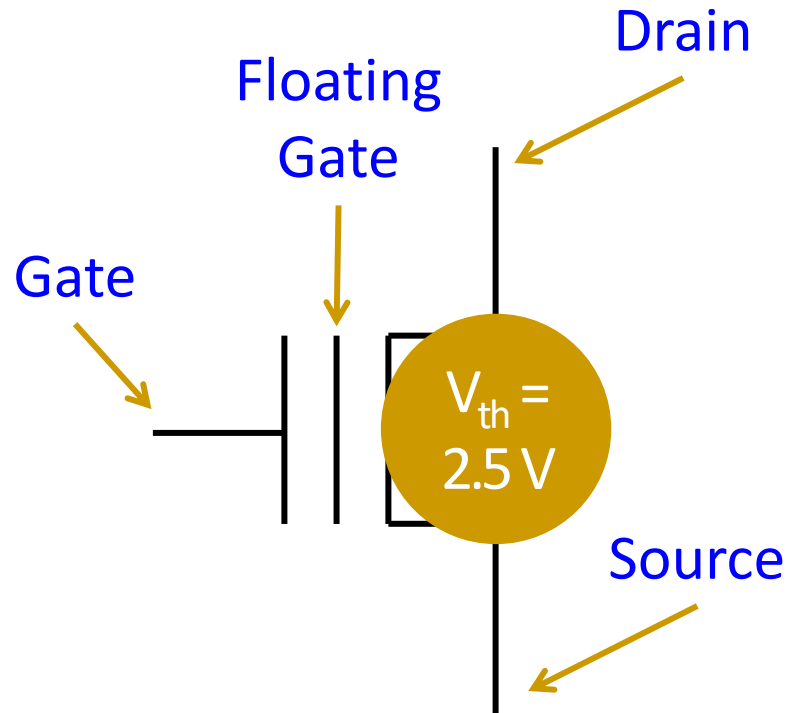


# Flash Cell Array



# Flash Cell

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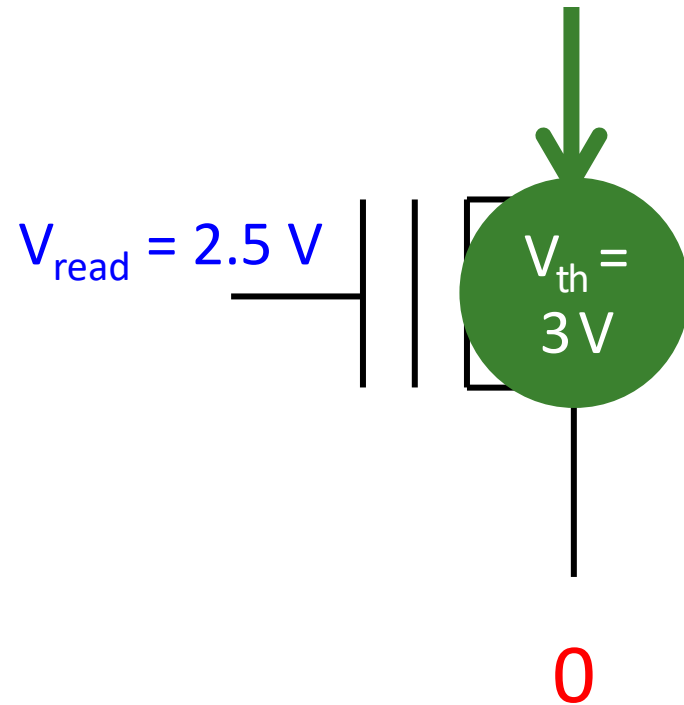
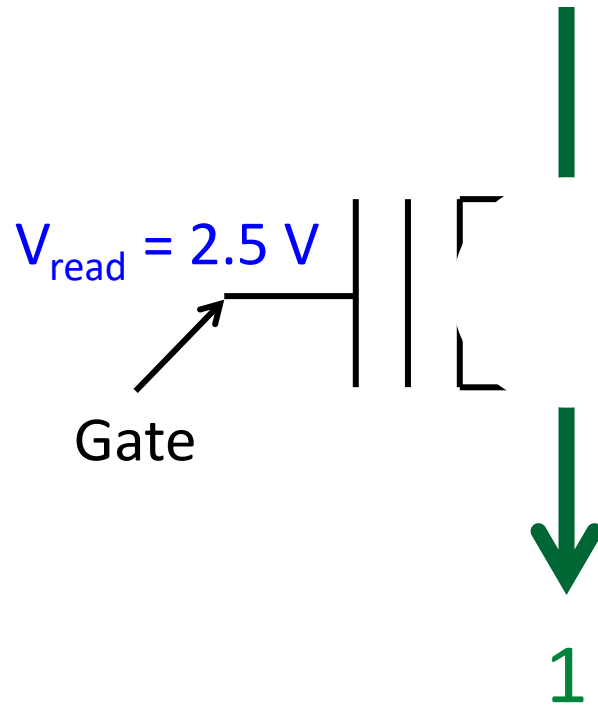


Floating Gate Transistor  
(Flash Cell)



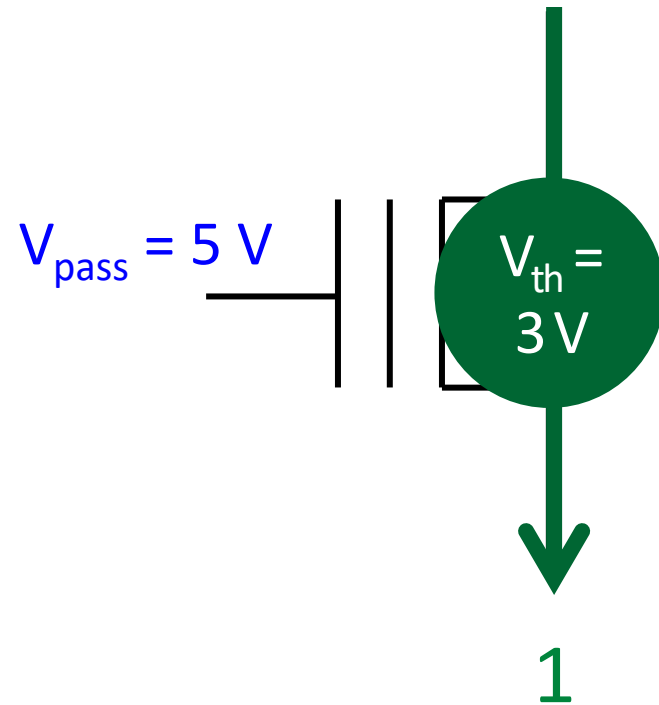
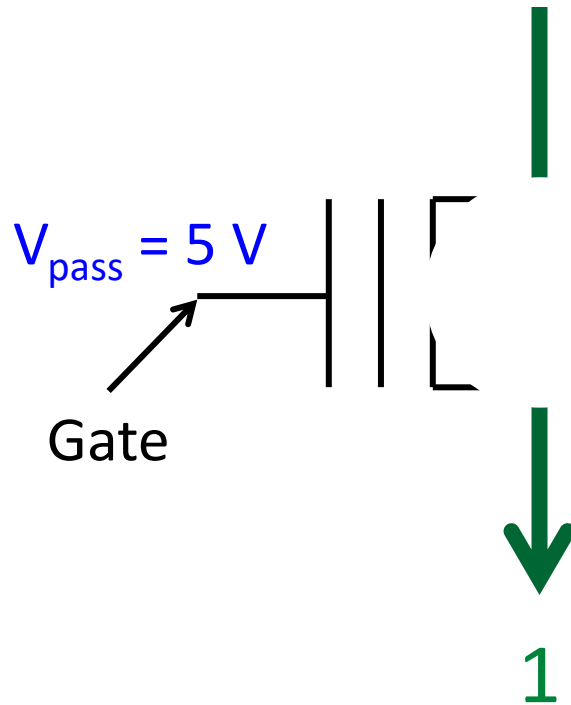
# Flash Read

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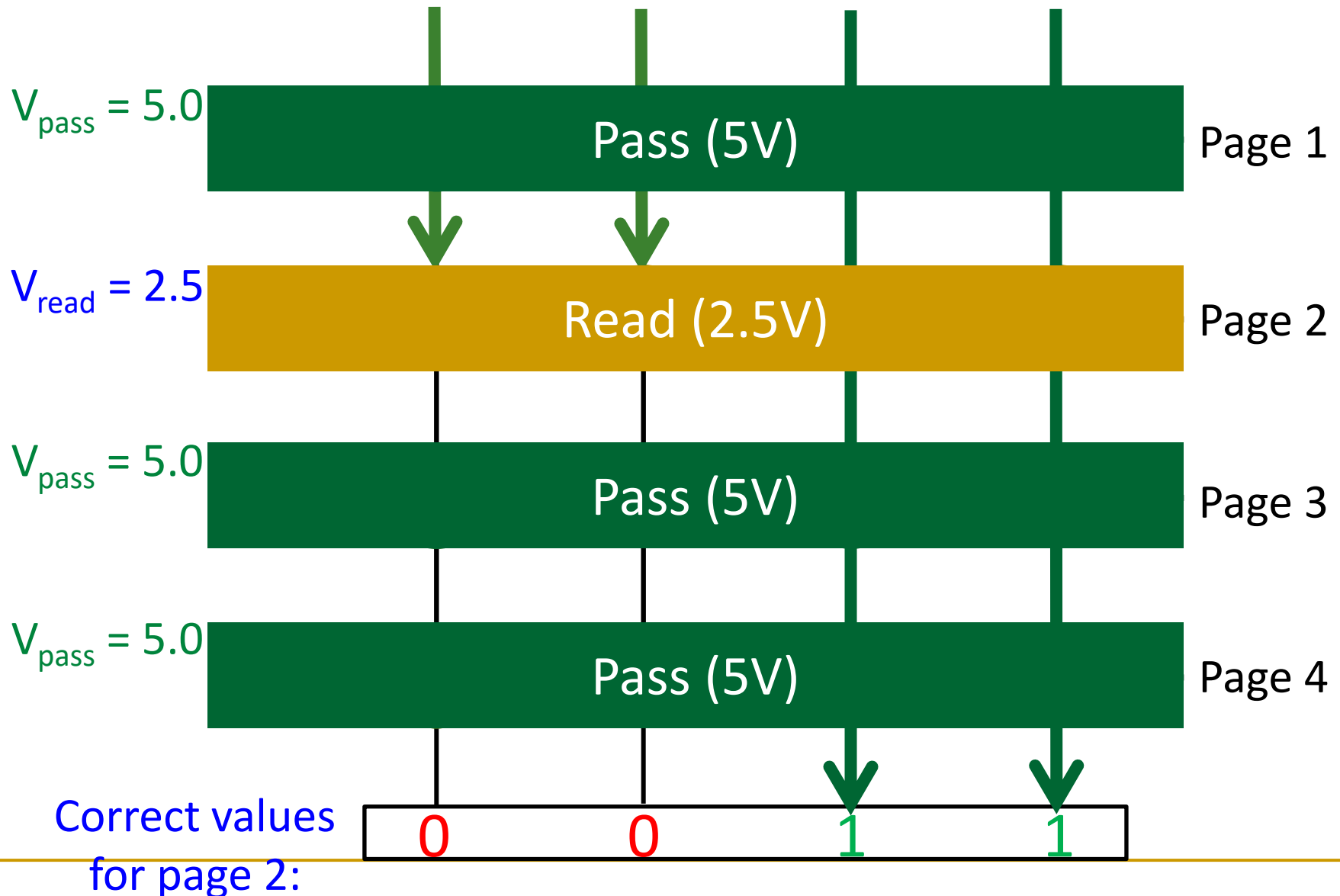


# Flash Pass-Through

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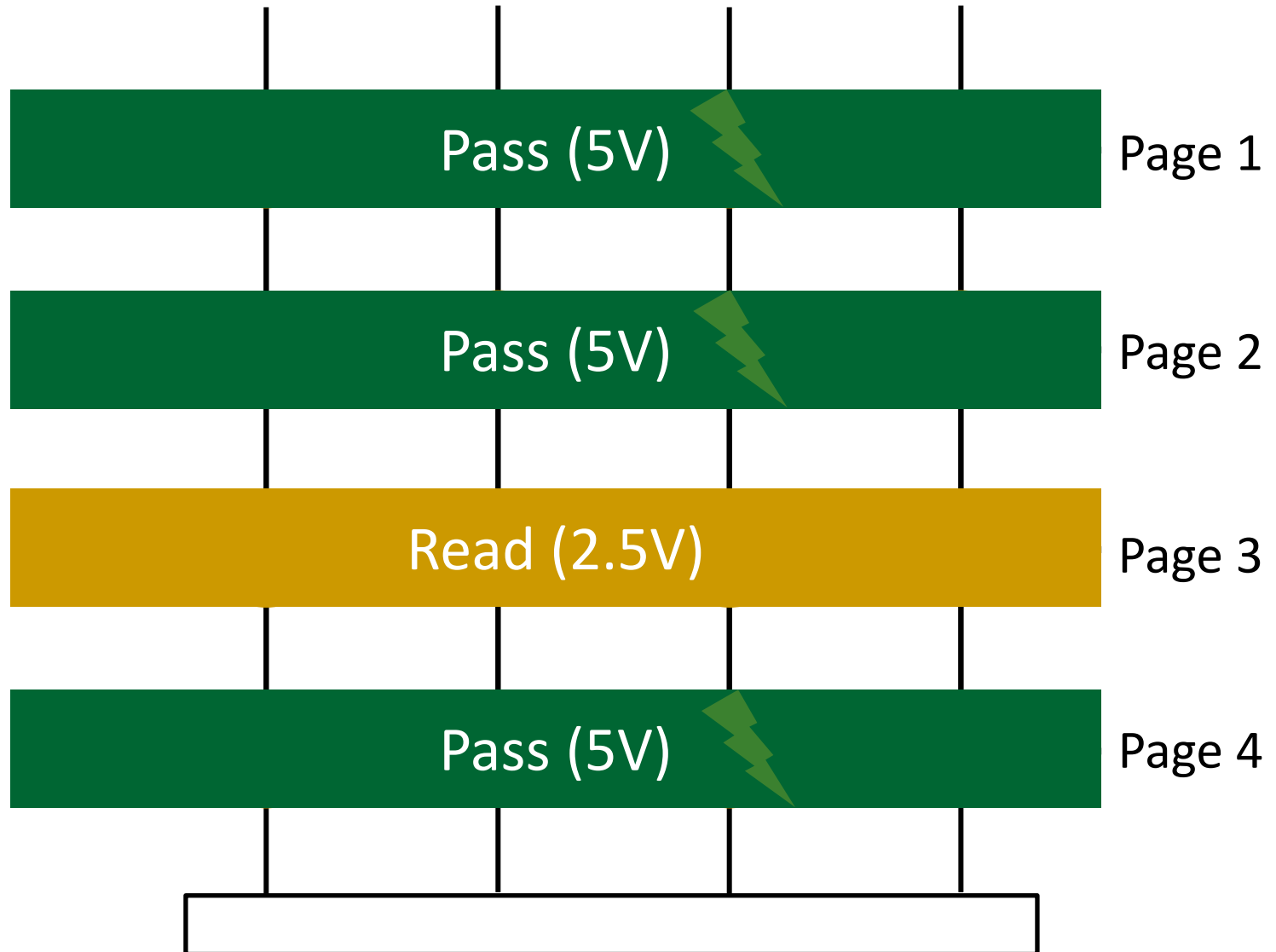


# Read from Flash Cell Array



# Read Disturb Problem: ‘Weak Programming’

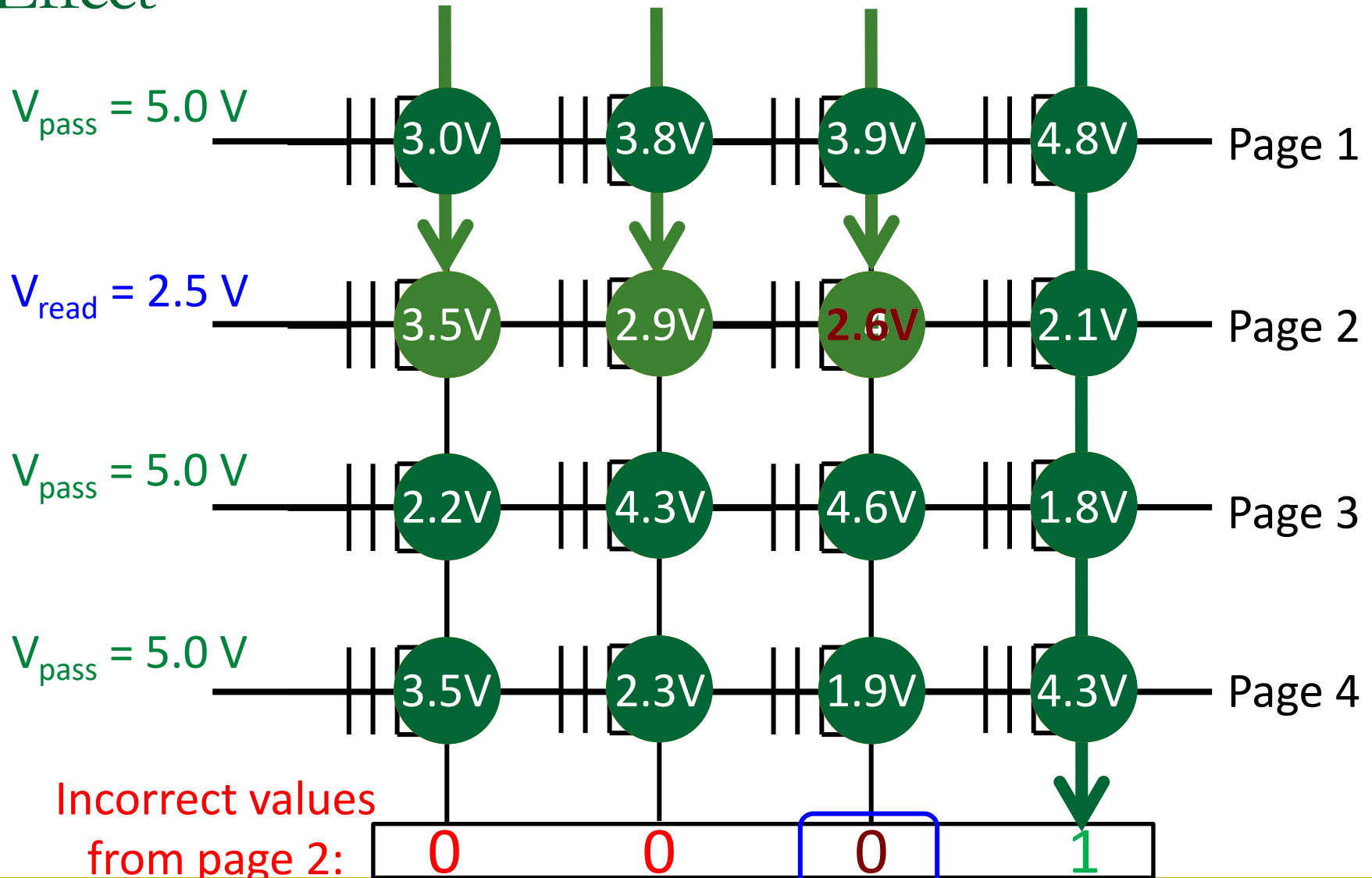
## Effect



Repeatedly read page 3 (or any page other than page 2)

# Read Disturb Problem: ‘Weak Programming’

## Effect



High pass-through voltage induces “weak-programming” effect<sub>133</sub>

# Executive Summary [DSN'15]

---

- ***Read disturb errors*** limit flash memory lifetime today
  - Apply a *high pass-through voltage* ( $V_{pass}$ ) to multiple pages on a read
  - Repeated application of  $V_{pass}$  can alter stored values in unread pages
- We **characterize read disturb** on real NAND flash chips
  - Slightly lowering  $V_{pass}$  greatly reduces read disturb errors
  - Some flash cells are more prone to read disturb
- **Technique 1: Mitigate** read disturb errors online
  - **$V_{pass}$  Tuning** dynamically finds and applies a lowered  $V_{pass}$  per block
  - Flash memory lifetime improves by 21%
- **Technique 2: Recover** after failure to prevent data loss

# Key Observation 1: Slightly lowering $V_{pass}$ greatly reduces read disturb errors

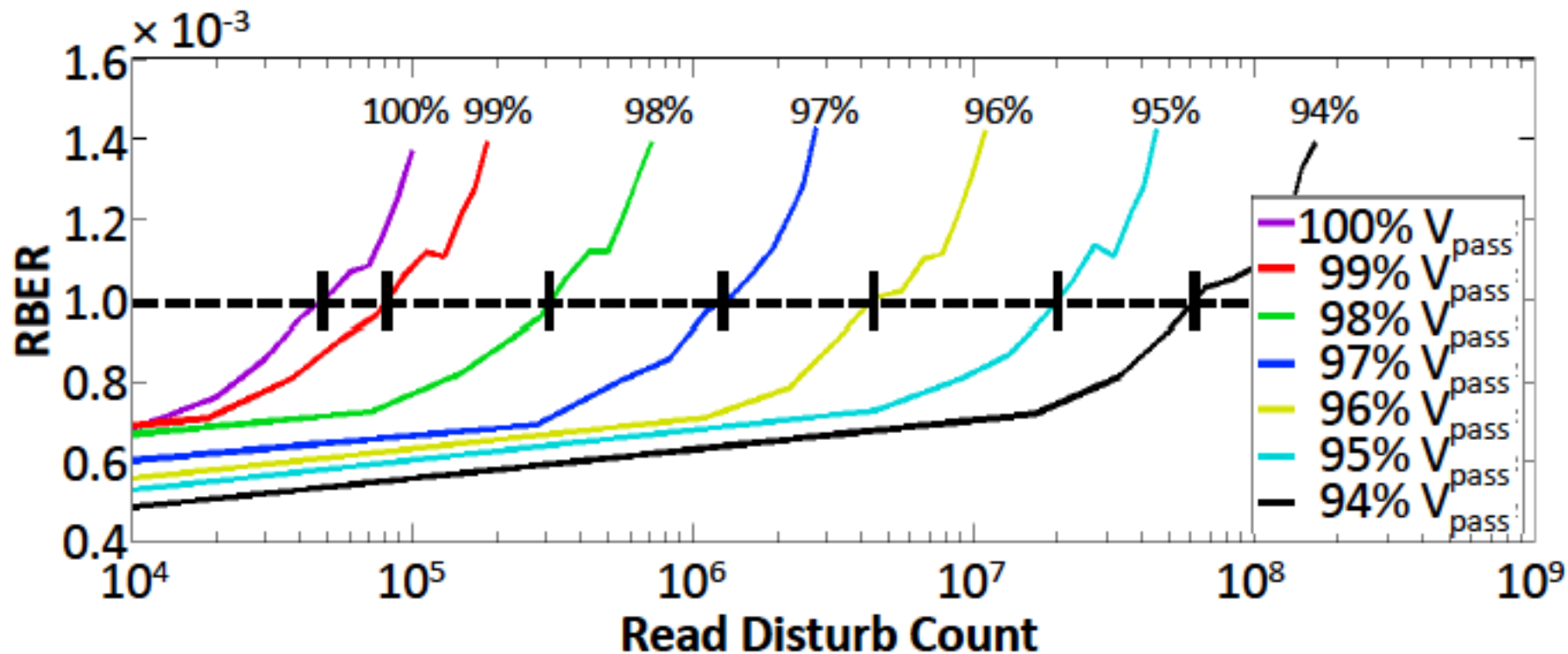


Fig. 11. Raw bit error rate vs. read disturb count for different  $V_{pass}$  values, for flash memory under 8K P/E cycles of wear.

# Outline

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- Background (Problem and Goal)
- Key Experimental Observations
- **Mitigation:  $V_{\text{pass}}$  Tuning**
- Recovery: Read Disturb Oriented Error Recovery
- Conclusion



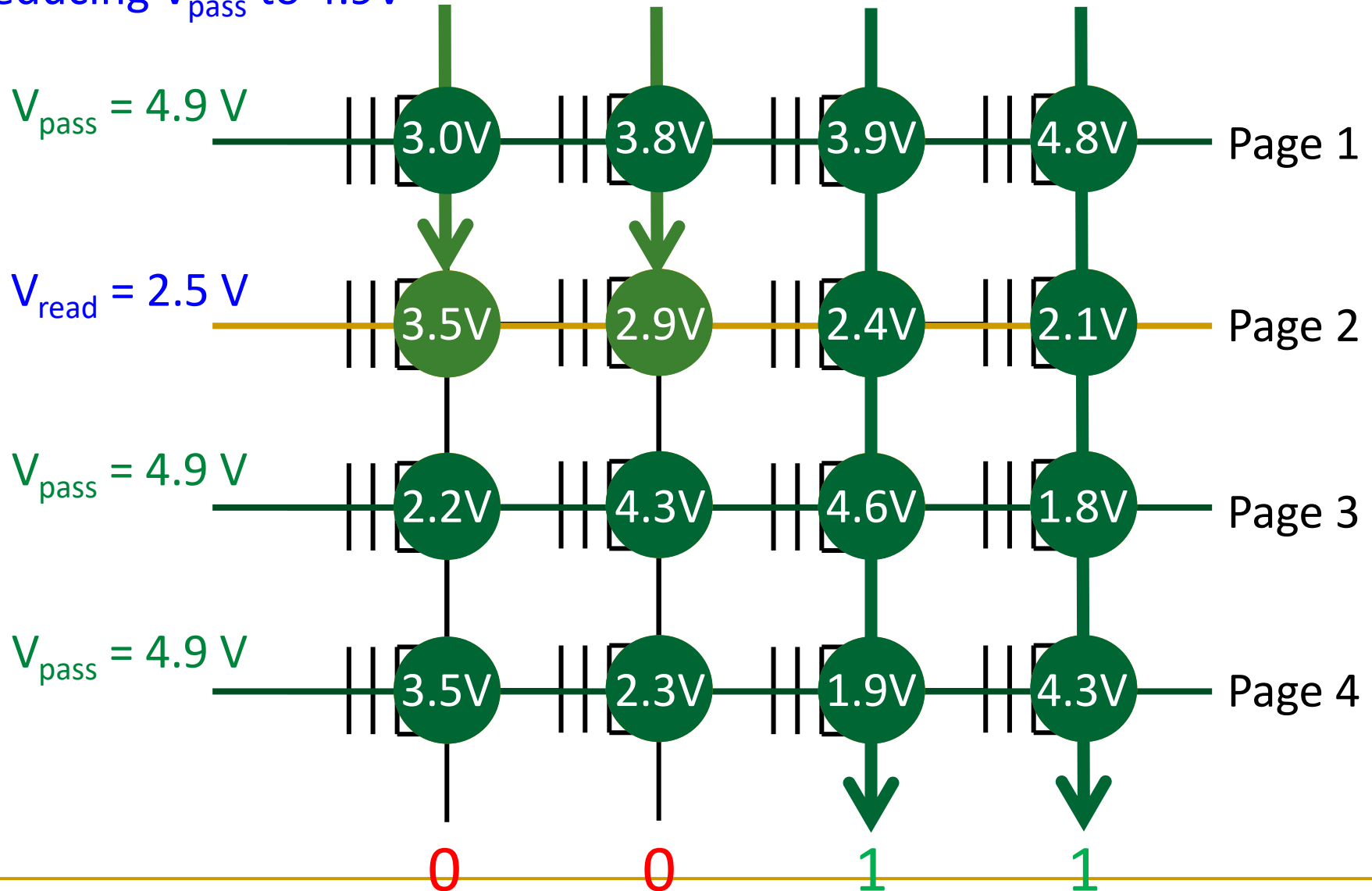
# Read Disturb Mitigation: $V_{\text{pass}}$ Tuning

---

- Key Idea: Dynamically find and apply a lowered  $V_{\text{pass}}$
- Trade-off for lowering  $V_{\text{pass}}$ 
  - + Allows more read disturbs
  - Induces more read errors

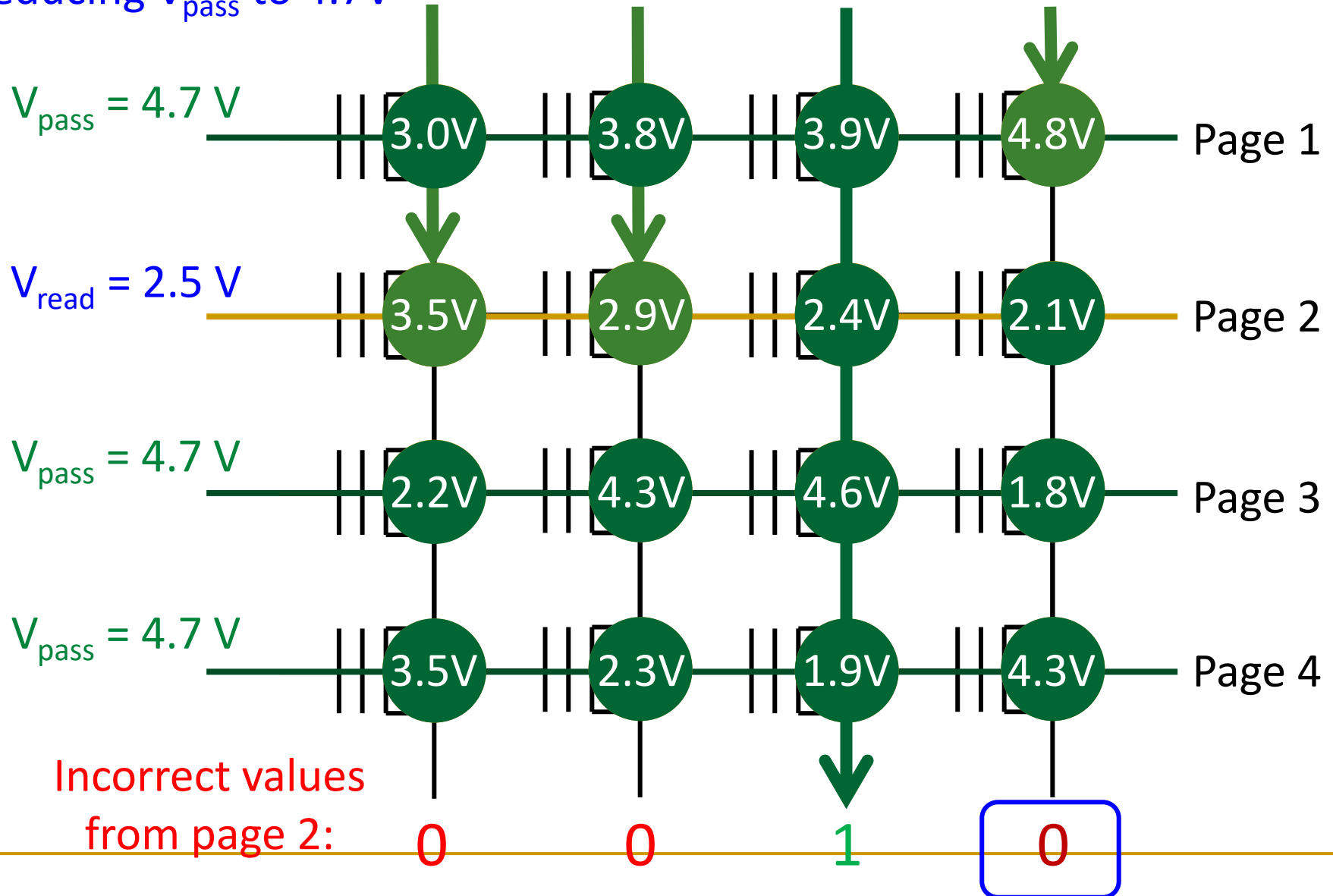
# Read Errors Induced by $V_{\text{pass}}$ Reduction

Reducing  $V_{\text{pass}}$  to 4.9V

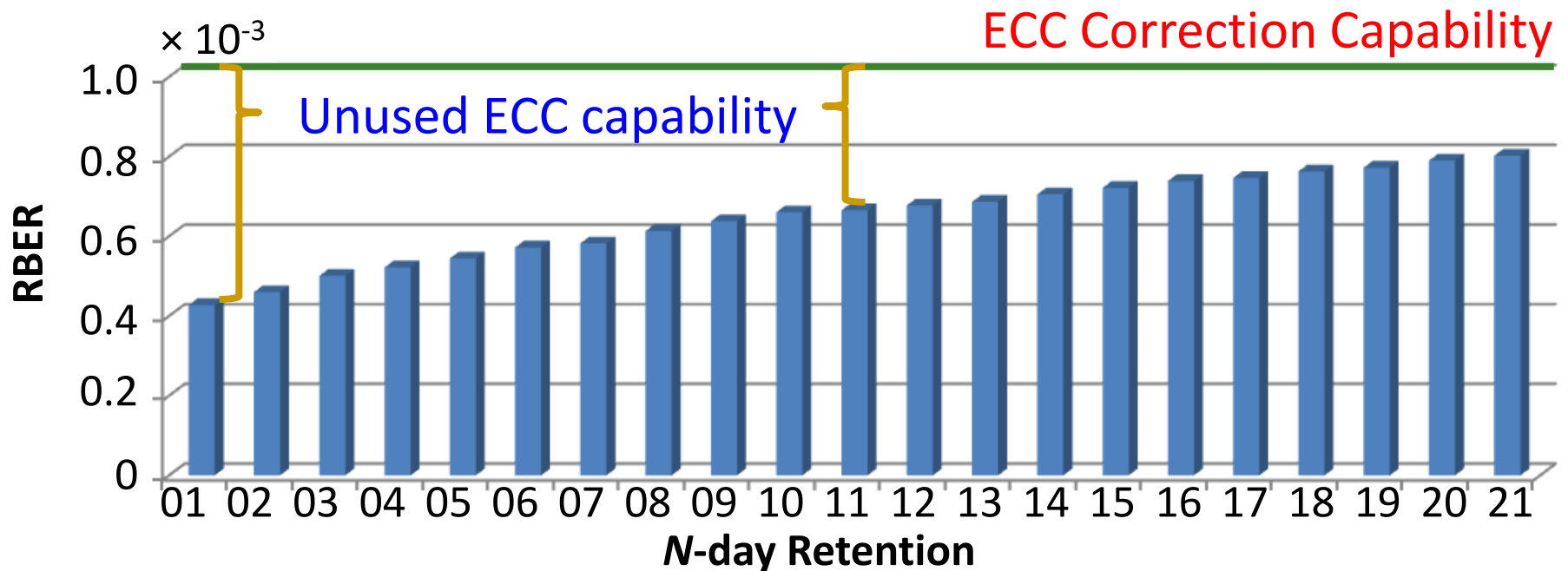


# Read Errors Induced by $V_{\text{pass}}$ Reduction

Reducing  $V_{\text{pass}}$  to 4.7V



# Utilizing the Unused ECC Capability



1. ECC provisioned for high retention “age”
2. Unused ECC capability can be used to fix read errors
3. Unused ECC capability decreases over retention age

Dynamically adjust  $V_{\text{pass}}$  so that read errors fully utilize the unused ECC capability

# $V_{\text{pass}}$ Reduction Trade-Off Summary

---

- Today: Conservatively set  $V_{\text{pass}}$  to a high voltage
  - Accumulates more read disturb errors at the end of each refresh interval
  - + No read errors
  
- Idea: Dynamically adjust  $V_{\text{pass}}$  to unused ECC capability
  - + Minimize read disturb errors
    - Control read errors to be tolerable by ECC
    - If read errors exceed ECC capability, read again with a higher  $V_{\text{pass}}$  to correct read errors

# $V_{\text{pass}}$ Tuning Steps

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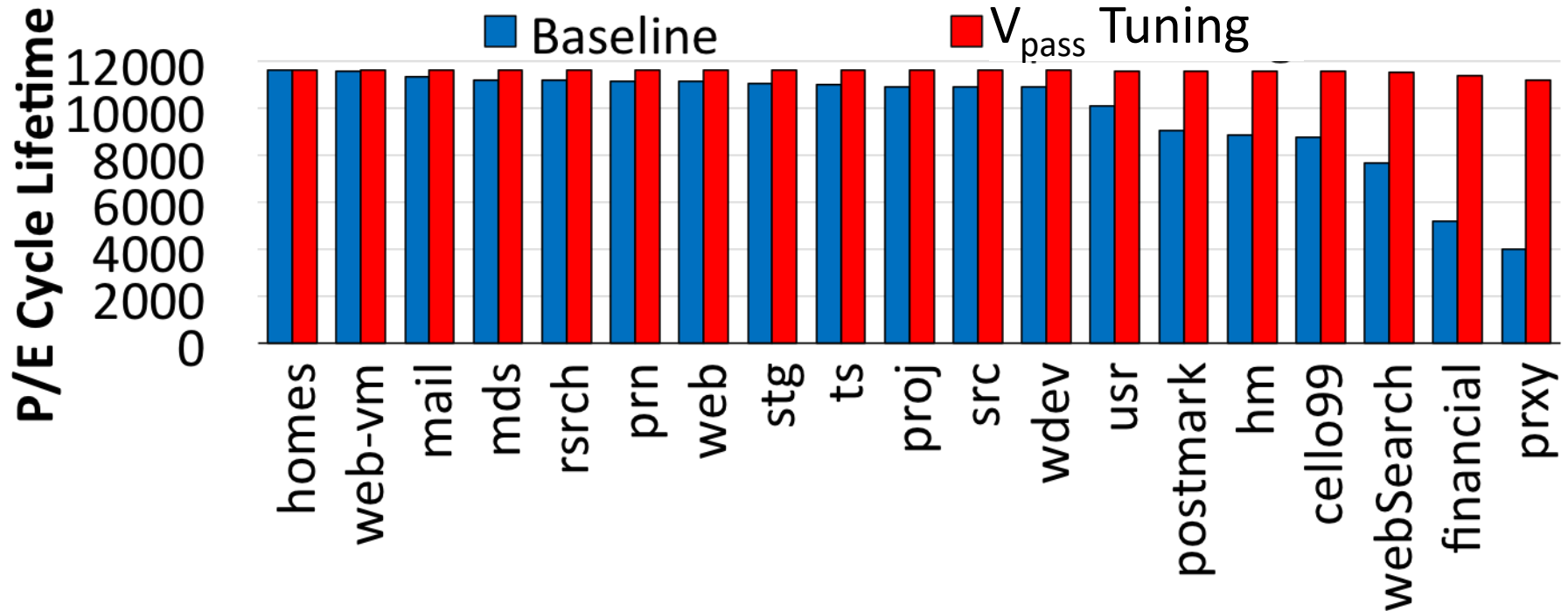
- Perform once for each block every day:
  1. **Estimate** *unused ECC capability (using retention age)*
  2. **Aggressively reduce**  $V_{\text{pass}}$  *until read errors exceeds ECC capability*
  3. **Gradually increase**  $V_{\text{pass}}$  *until read error becomes just less than ECC capability*

# Evaluation of $V_{\text{pass}}$ Tuning

---

- 19 real workload I/O traces
- Assume 7-day refresh period
- Similar methodology as before to determine acceptable  $V_{\text{pass}}$  reduction
- Overhead for a 512 GB flash drive:
  - 128 KB storage overhead for per-block  $V_{\text{pass}}$  setting and worst-case page
  - 24.34 sec/day average  $V_{\text{pass}}$  Tuning overhead

# $V_{\text{pass}}$ Tuning Lifetime Improvements

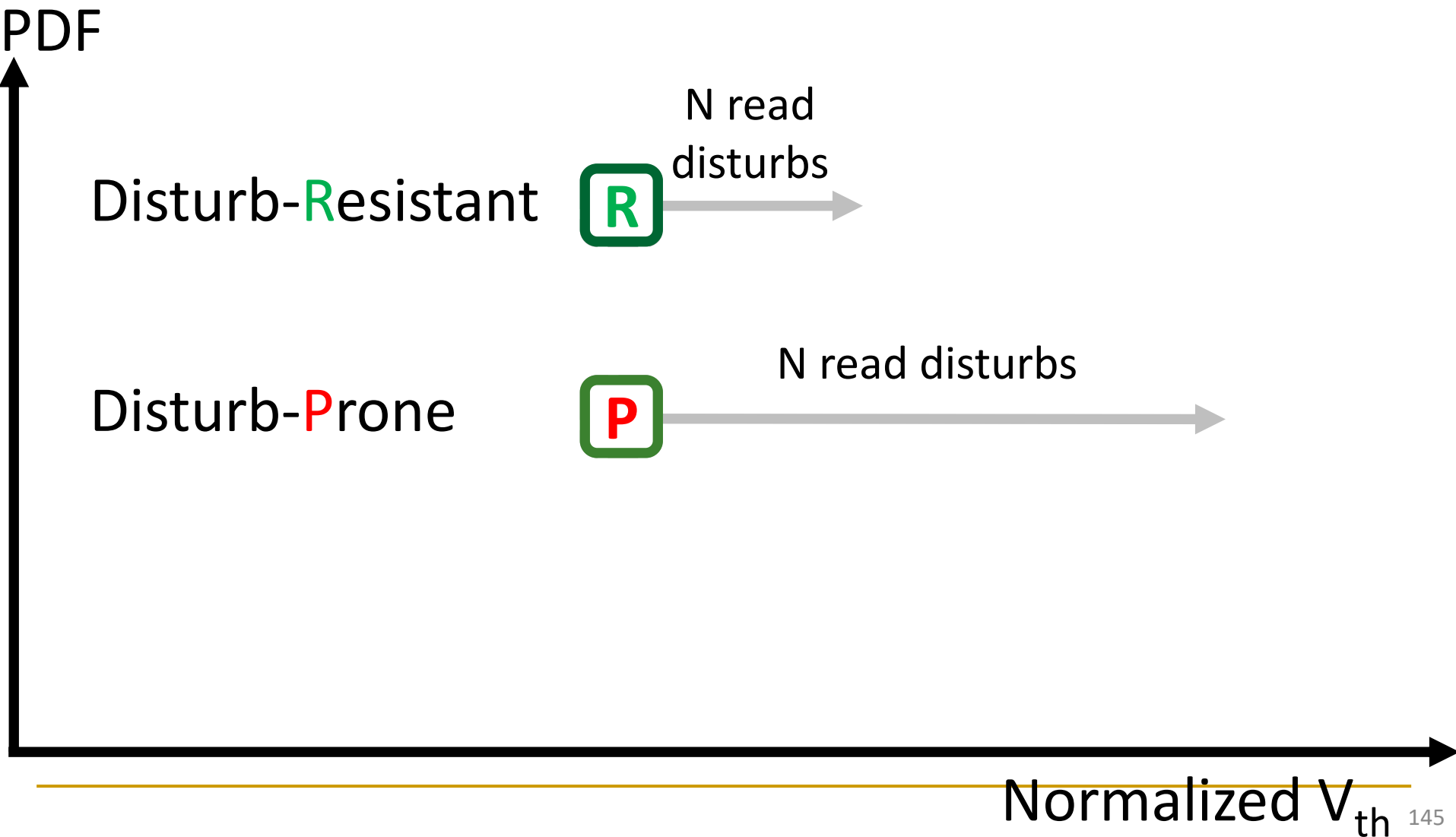


Average lifetime improvement: 21.0%



# Read Disturb Prone vs. Resistant Cells

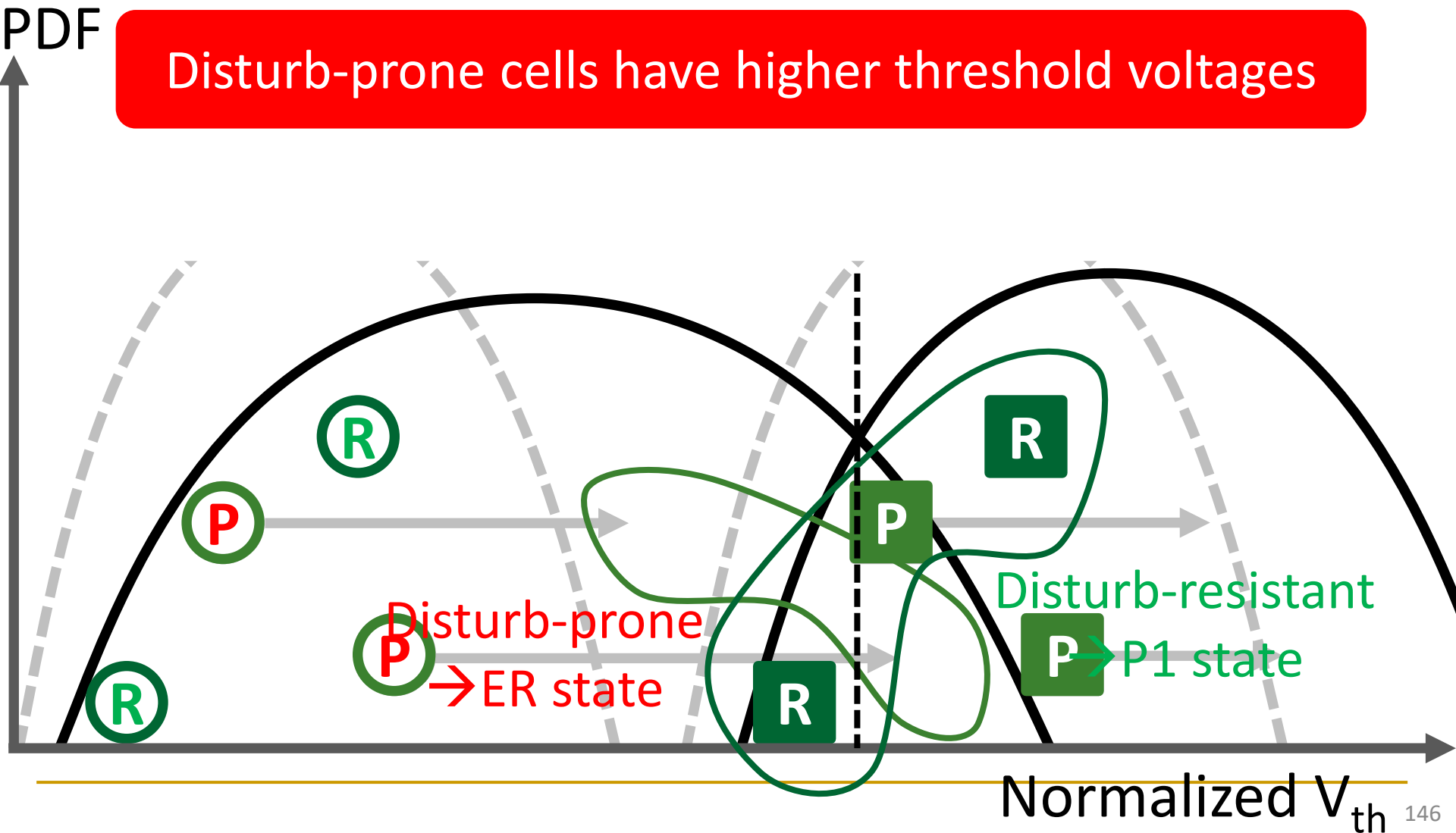
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# Observation 2: Some Flash Cells Are More Prone to Read Disturb

After 250K read disturbs:

Disturb-prone cells have higher threshold voltages



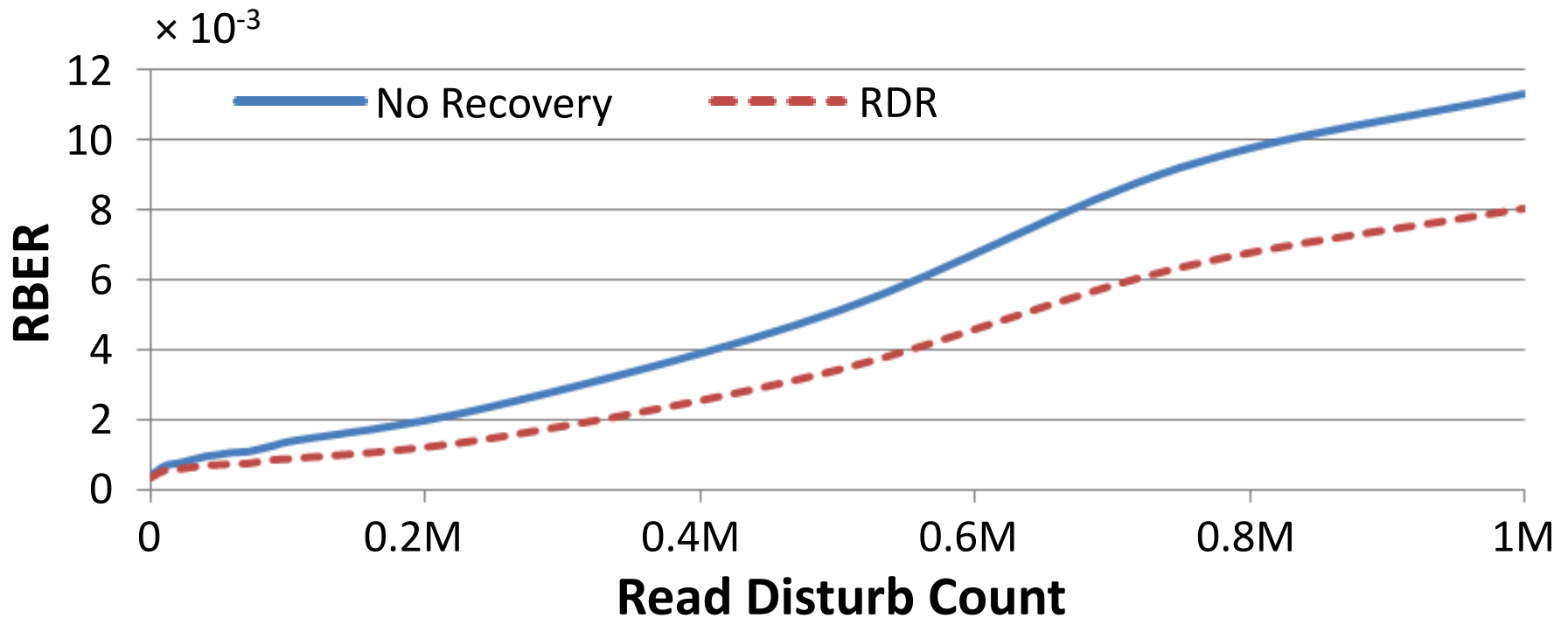
# Read Disturb Oriented Error Recovery (RDR)

---

- Triggered by an uncorrectable flash error
  - Back up all valid data in the faulty block
  - Disturb the faulty page 100K times (more)
  - Compare  $V_{th}$ 's before and after read disturb
  - Select cells susceptible to flash errors ( $V_{ref}-\sigma < V_{th} < V_{ref}+\sigma$ )
  - Predict among these susceptible cells
    - Cells with more  $V_{th}$  shifts are disturb-prone → Lower  $V_{th}$  state
    - Cells with less  $V_{th}$  shifts are disturb-resistant → Higher  $V_{th}$  state

Reduces total error count by up to 36% @ 1M read disturbs  
ECC can be used to correct the remaining errors

# RDR Evaluation



Reduces total error counts by up to 36% @ 1M read disturbs  
ECC can be used to correct the remaining errors

# More on Flash Read Disturb Errors [DSN'15]

---

- Yu Cai, Yixin Luo, Saugata Ghose, Erich F. Haratsch, Ken Mai, and Onur Mutlu,  
**"Read Disturb Errors in MLC NAND Flash Memory: Characterization and Mitigation"**  
*Proceedings of the 45th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*, Rio de Janeiro, Brazil, June 2015.

## Read Disturb Errors in MLC NAND Flash Memory: Characterization, Mitigation, and Recovery

Yu Cai, Yixin Luo, Saugata Ghose, Erich F. Haratsch\*, Ken Mai, Onur Mutlu  
Carnegie Mellon University, \*Seagate Technology  
[yucaicai@gmail.com](mailto:yucaicai@gmail.com), {yixinluo, ghose, kenmai, onur}@cmu.edu

# Agenda

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  - Retention Error Handling
  - 3D NAND Flash Memory Reliability
- Summary

# Data Retention in Flash Memory

---

Characterize

retention loss in real NAND chip

Optimize

read performance for old data

Recover

old data after failure



# *An unfortunate tale about Samsung's SSD 840*

## read performance degradation

An avalanche of reports emerged last September, when owners of the usually speedy Samsung SSD 840 and SSD 840 EVO detected the drives were no longer performing as they used to.

The issue has to do with older blocks of data: reading old files consistently slower than normal as slow as 30MB/s whereas newly-written files ones used in benchmarks, perform as fast as new – are 500 MB/s for the well regarded SSD 840 EVO. The reason no one had noticed (we reviewed the drive back in September 2013) is that data has to be several weeks old to show the problem. Samsung promptly admitted the issue and proposed a fix.

---

# Why is old data slower?



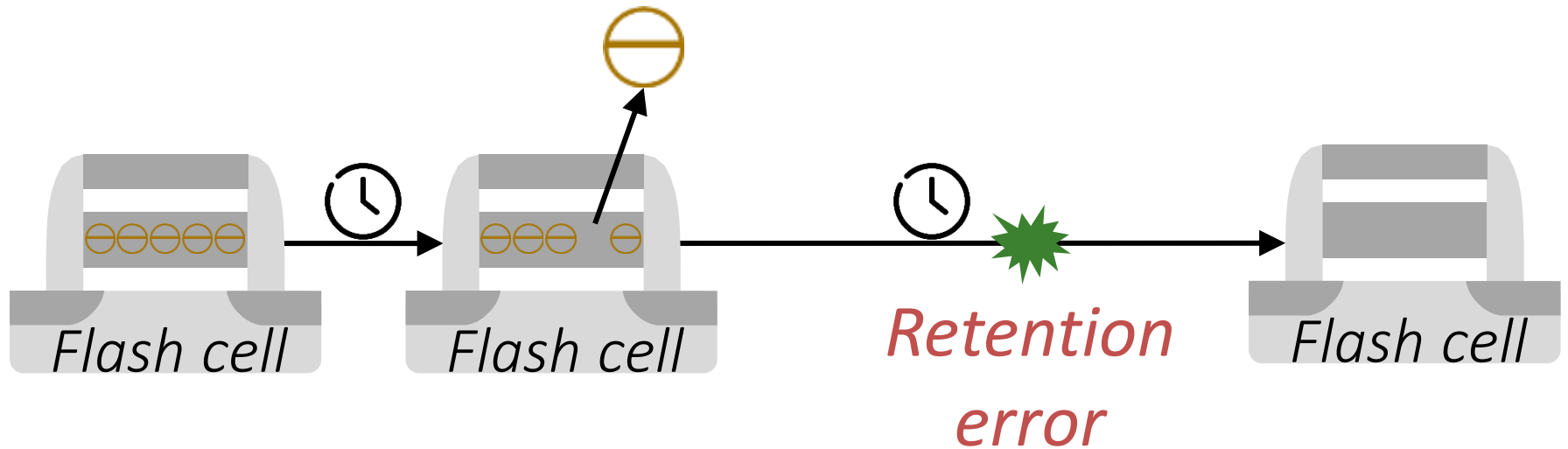
© Marien Couët 2013

Retention  
loss!

# Retention loss

---

*Charge leakage over time*

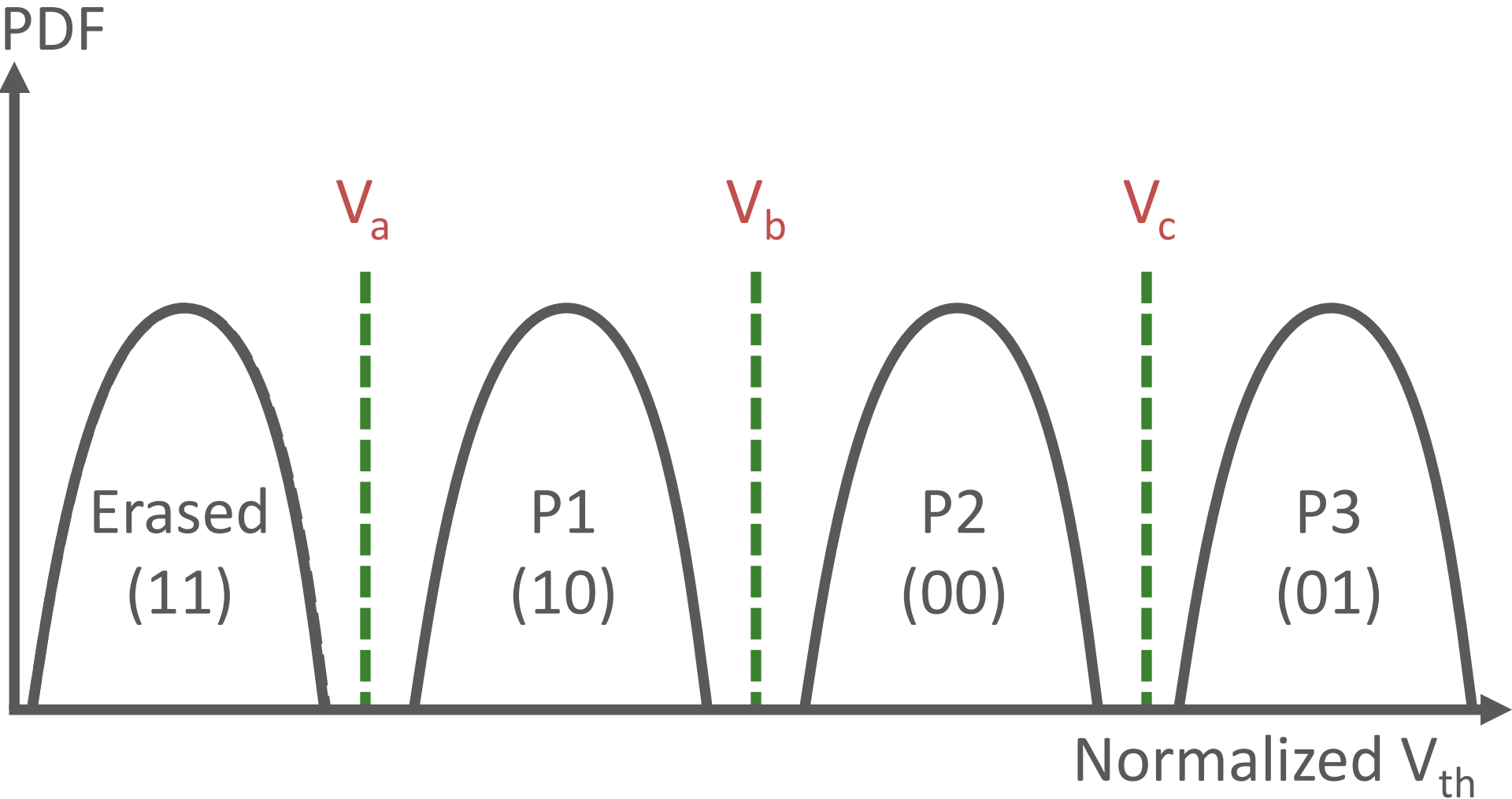


*One dominant source of flash  
memory errors [DATE '12, ICCD '12]*

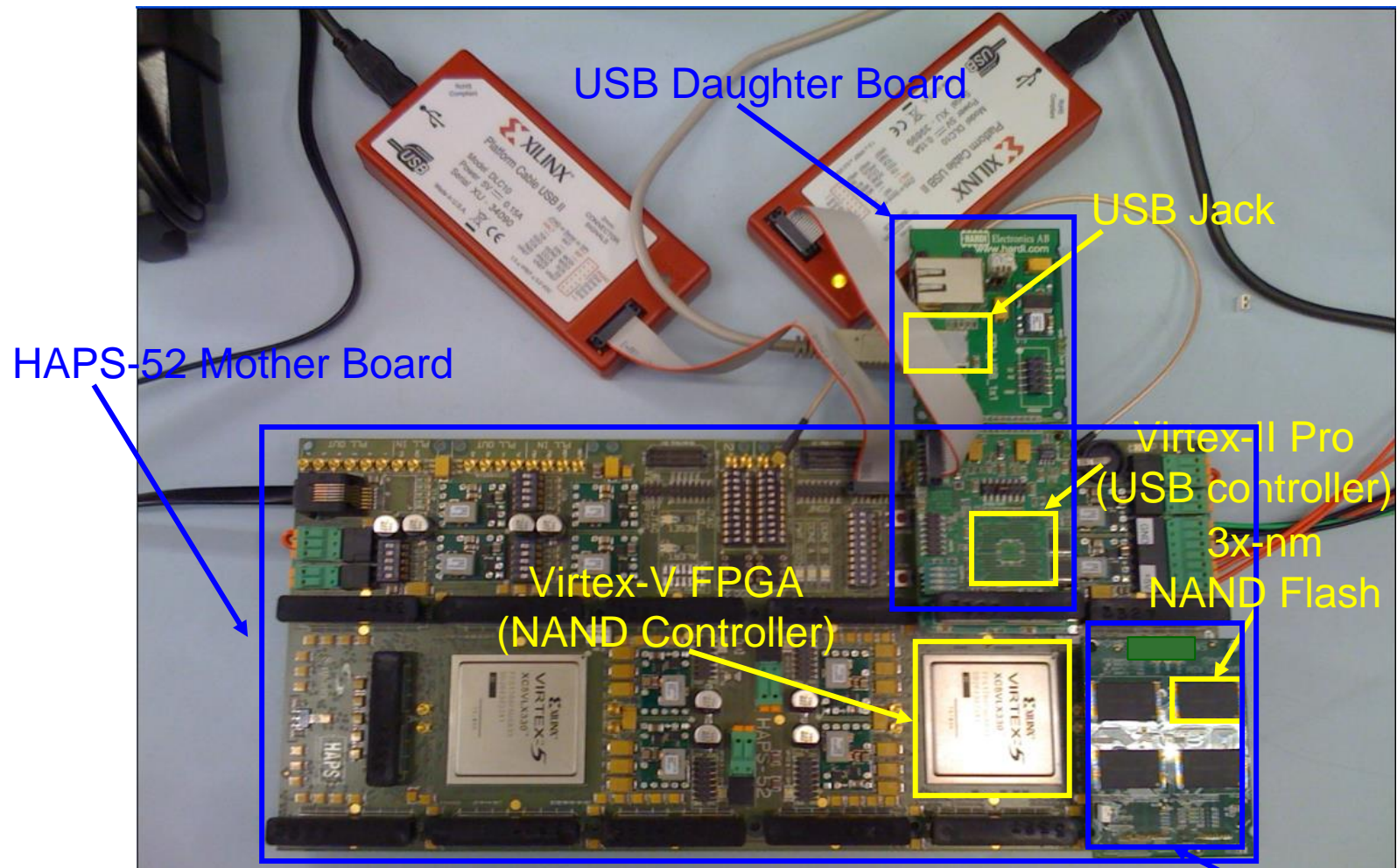
*Side effect: Longer read latency*

# Multi-Level Cell (MLC)

## threshold voltage distribution



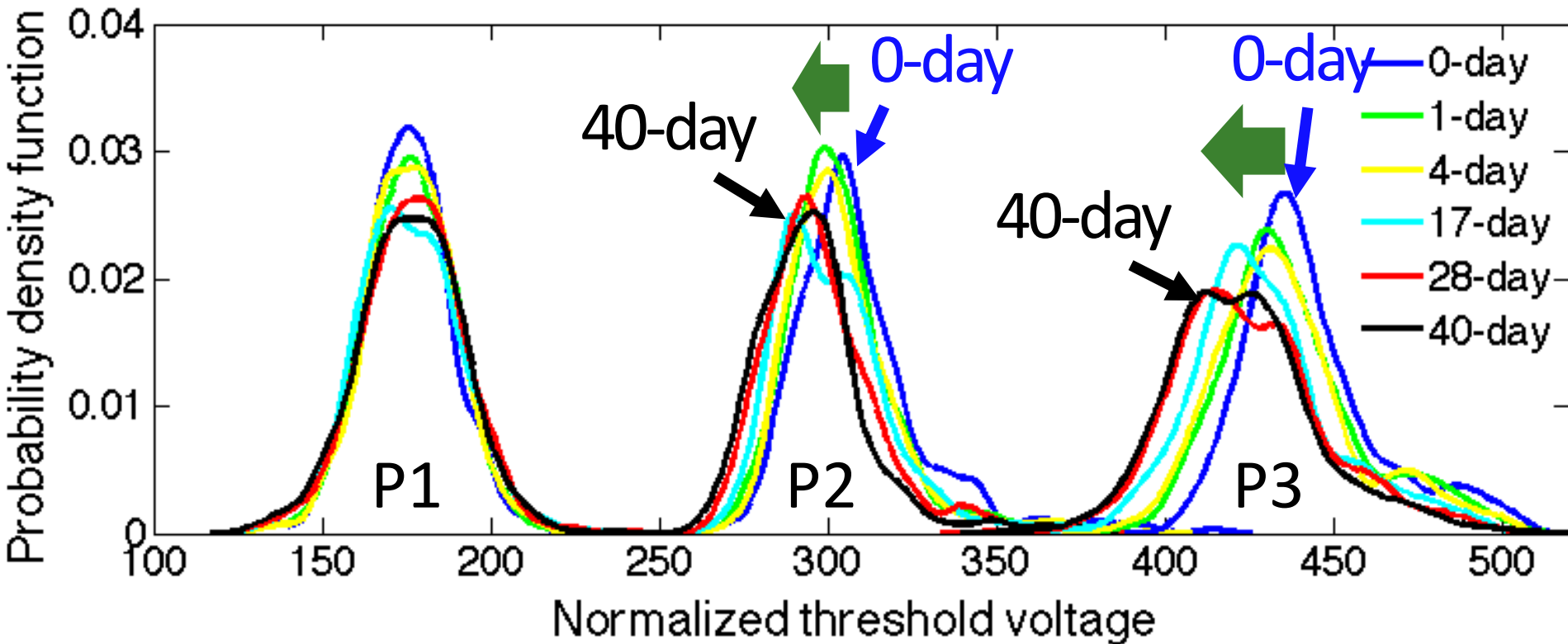
# Experimental Testing Platform



[Cai+, FCCM 2011, DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, DSN 2015, HPCA 2015]

NAND Daughter Board

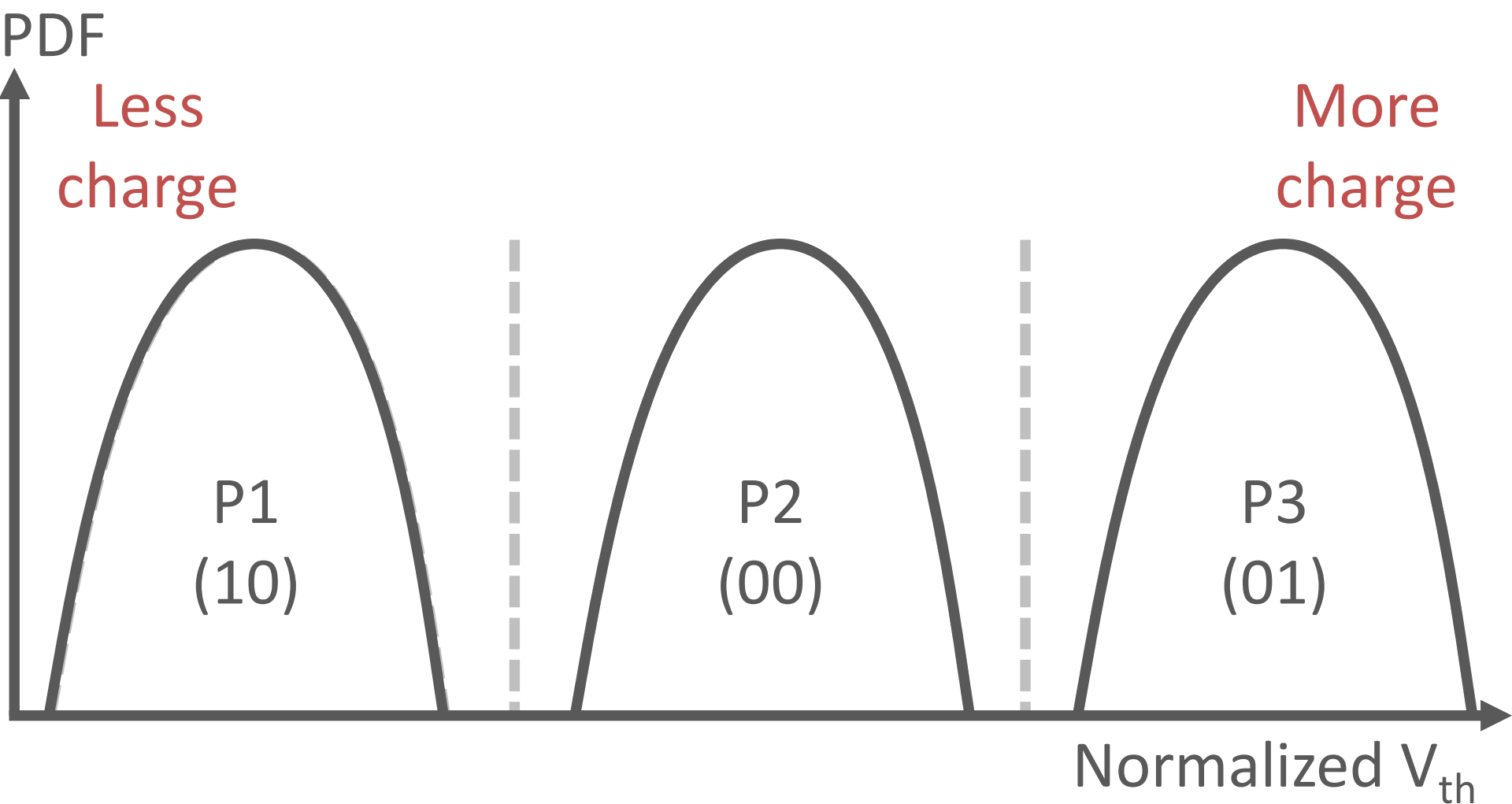
# Characterized threshold voltage distribution



Finding: Cell's threshold voltage decreases over time

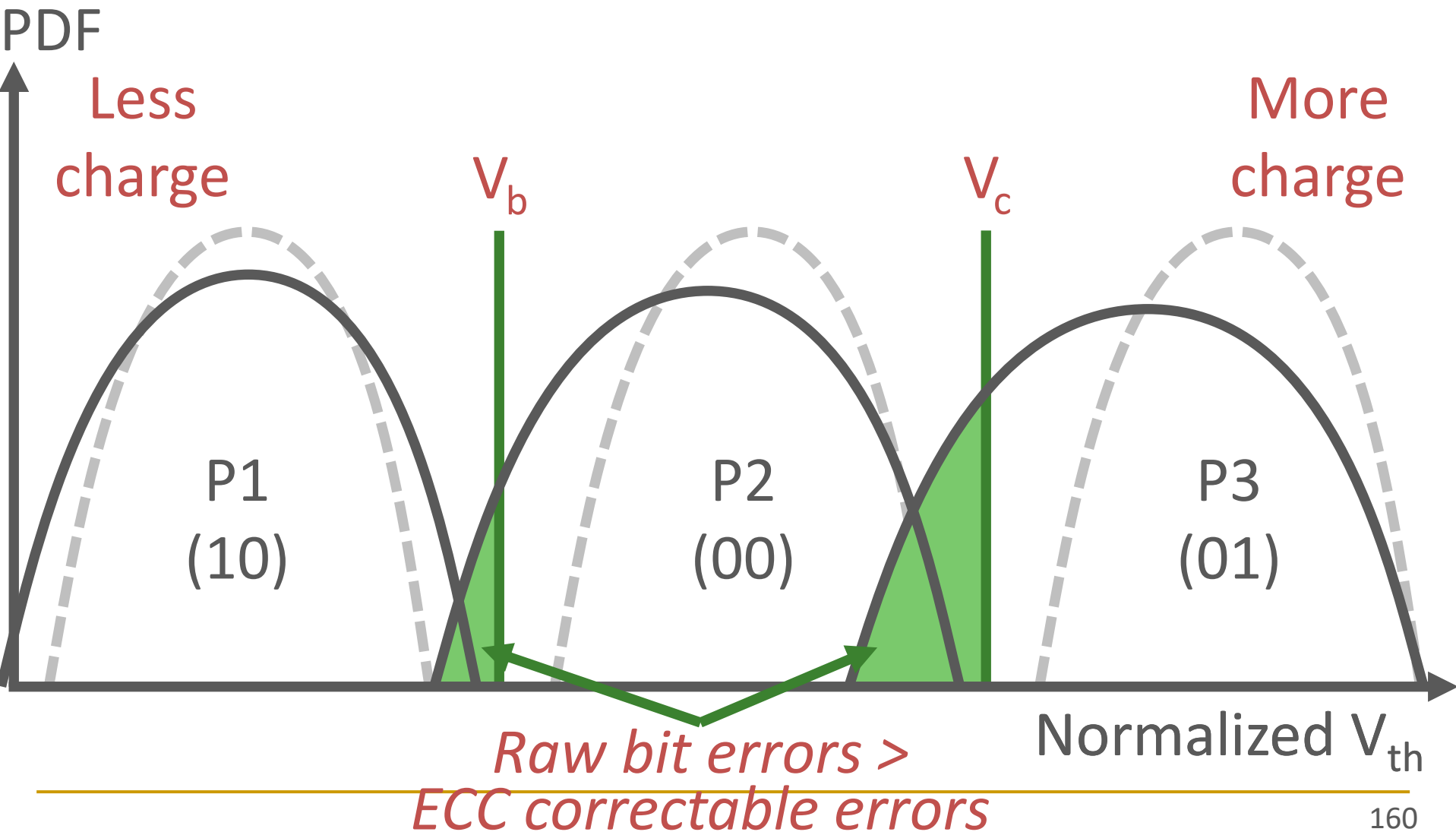
# Threshold voltage reduces over time

Old data



# First read attempt fails

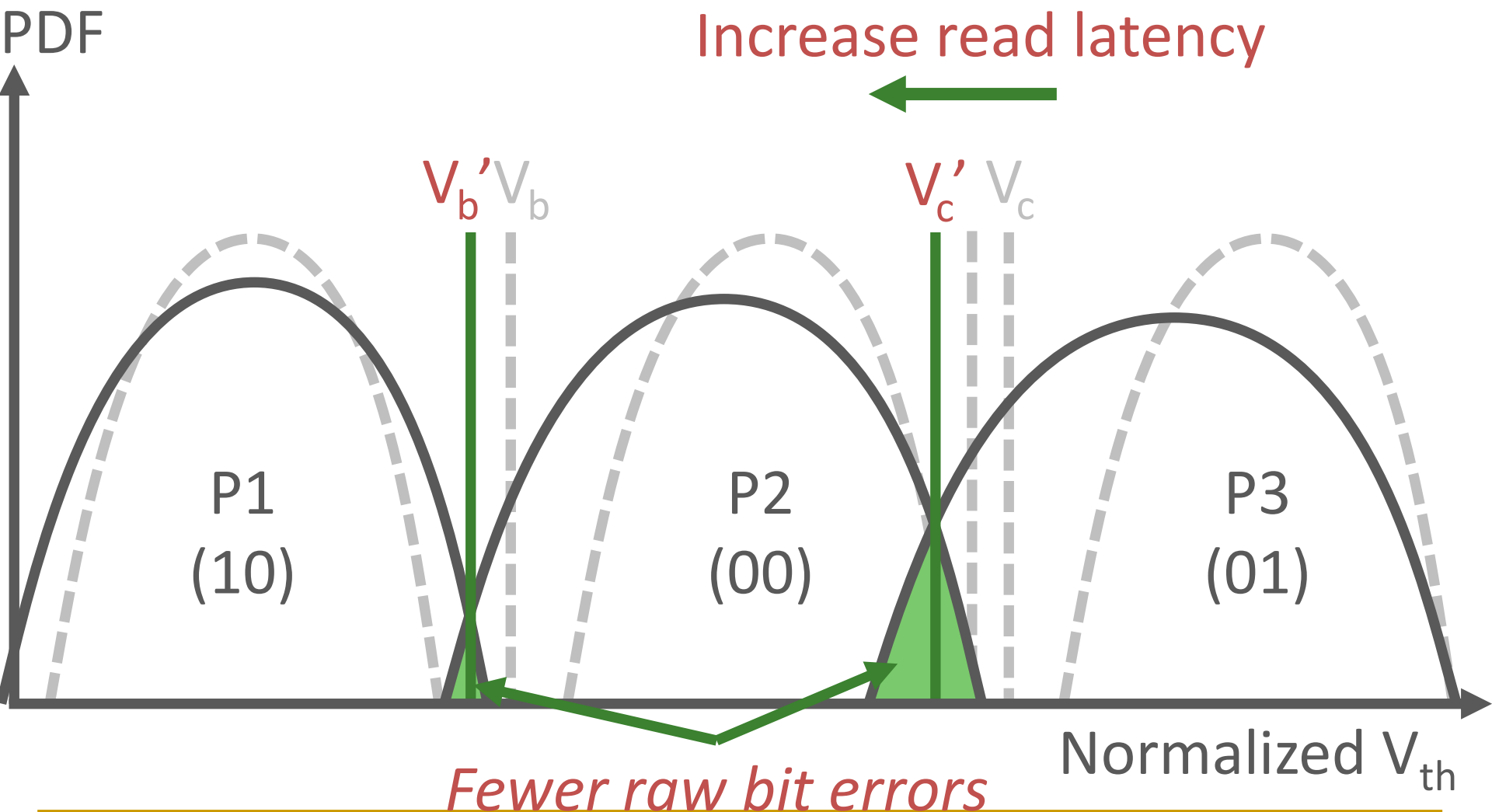
Old data





# Read-retry

Old data



# Why is old data slower?

---

## Retention loss

- Leak charge over time
  - Generate retention errors
    - Require read-retry
      - Longer read latency

---

Characterize

retention loss in real NAND chip

Optimize

read performance for old data

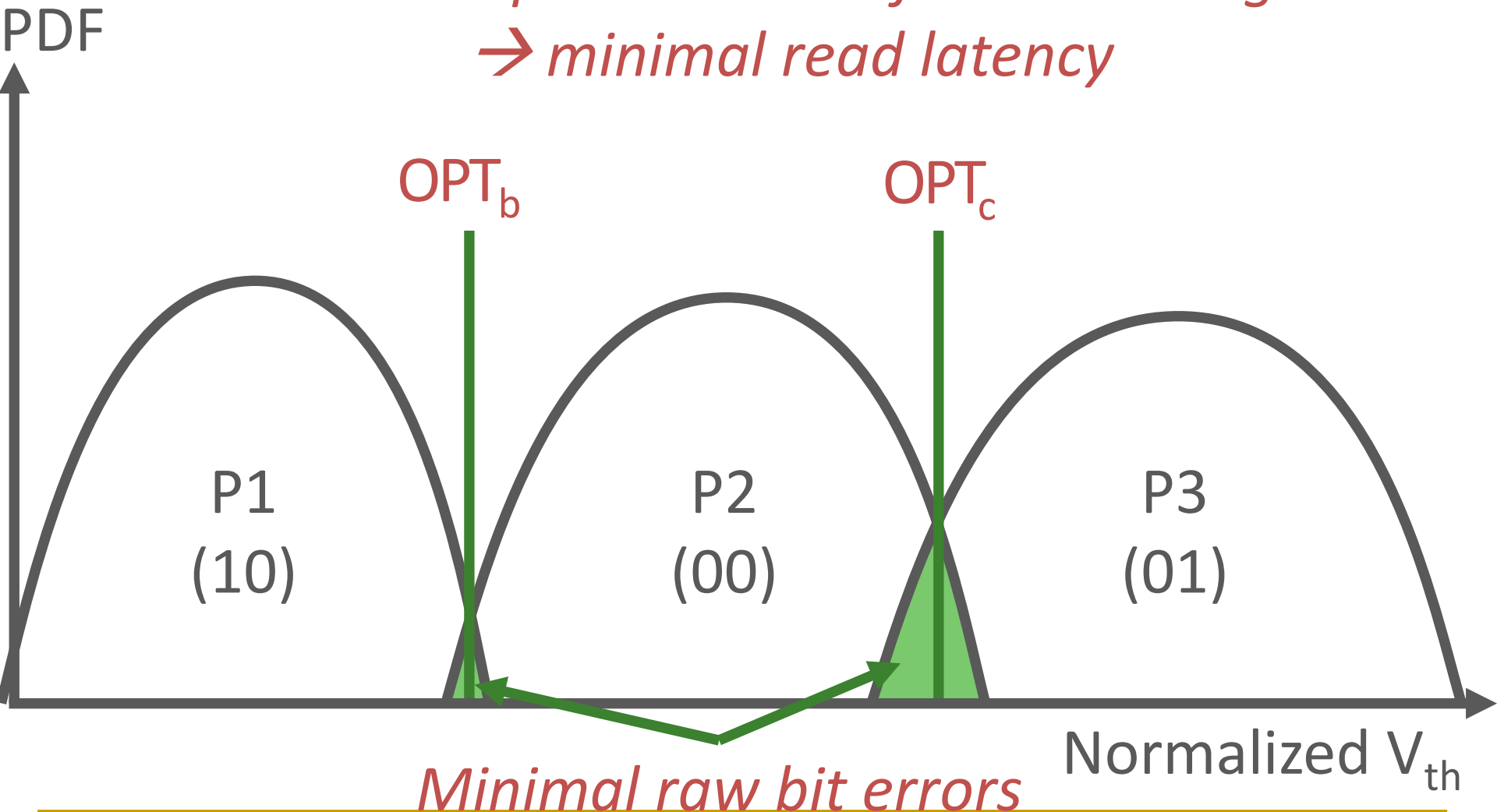
Recover

old data after failure

# The ideal read voltage

Old data

*OPT: Optimal read reference voltage  
→ minimal read latency*



# In reality

---

- OPT changes over time due to retention loss
- Luckily, OPT change is:
  - Gradual
  - Uni-directional (decreases over time)

# Retention Optimized Reading (ROR)

---

## Components:

### 1. Online pre-optimization algorithm

- ❑ Learns and records OPT
- ❑ Performs in the background once every day

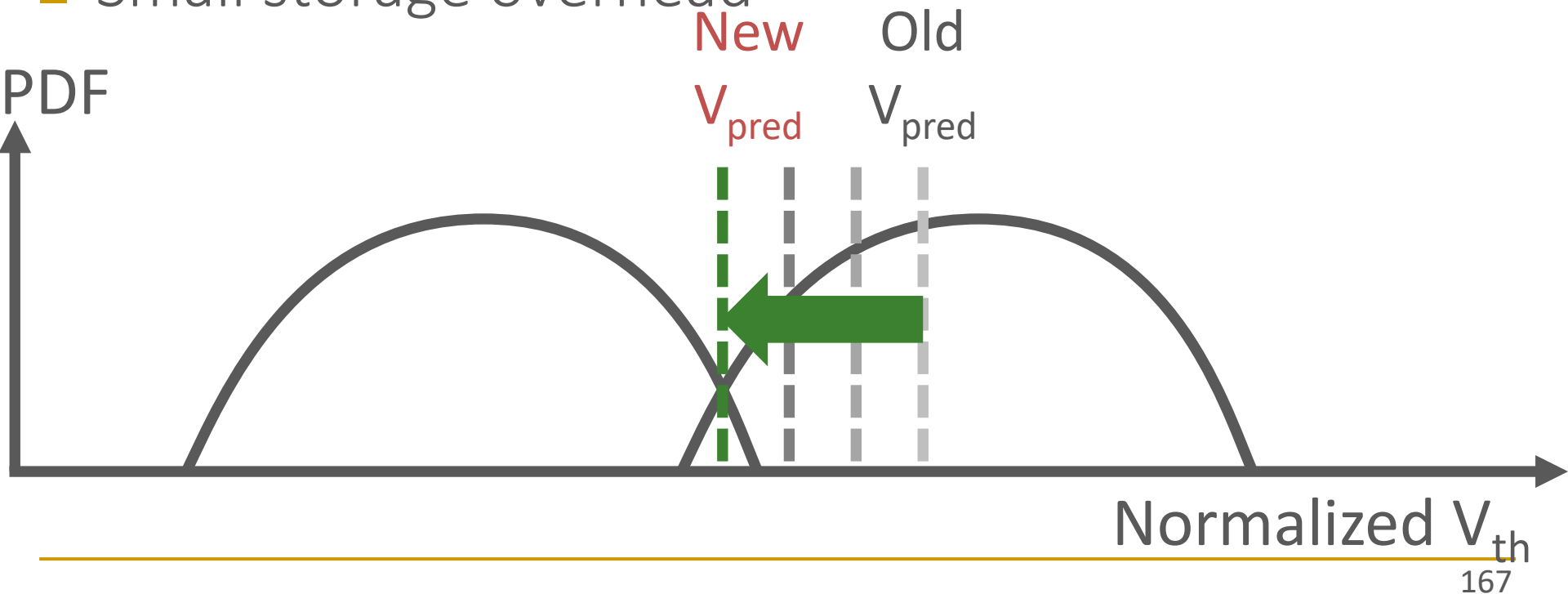
### 2. Simpler read-retry technique

- ❑ If recorded OPT is out-of-date, read-retry with *lower* voltage

# 1. Online Pre-Optimization Algorithm

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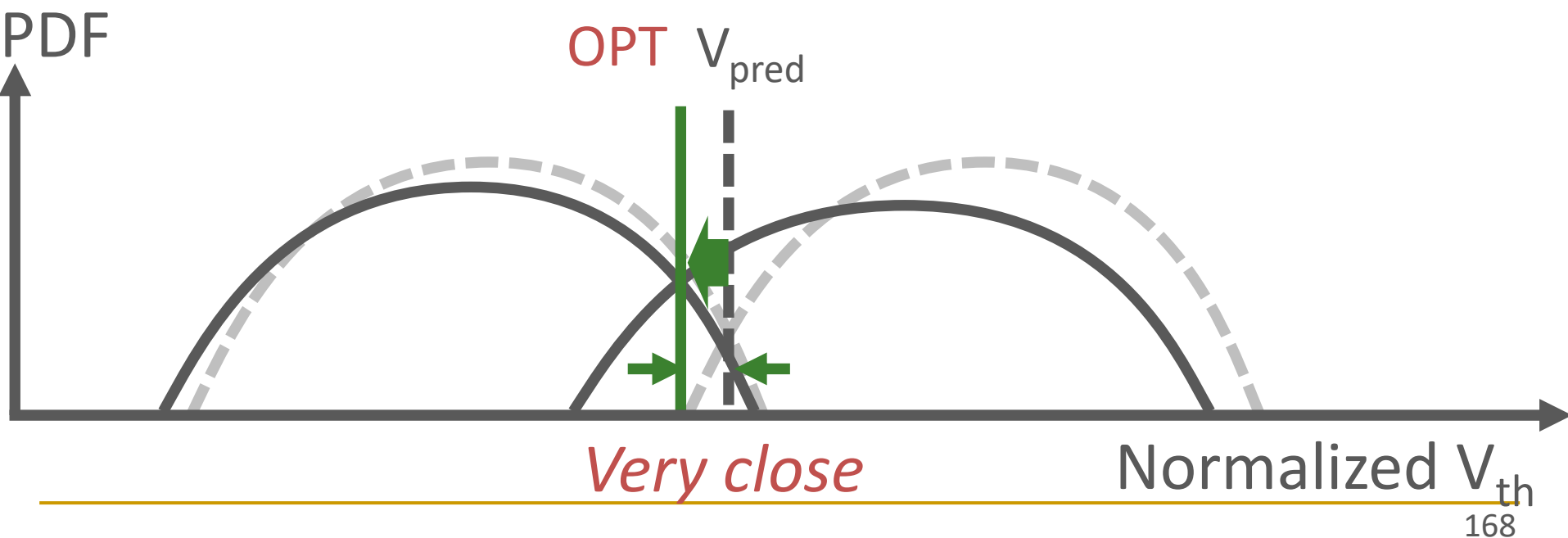
- Triggered periodically (e.g., per day)
- Find and record an OPT as per-block  $V_{\text{pred}}$
- Performed in background
- Small storage overhead



## 2. Improved Read-Retry Technique

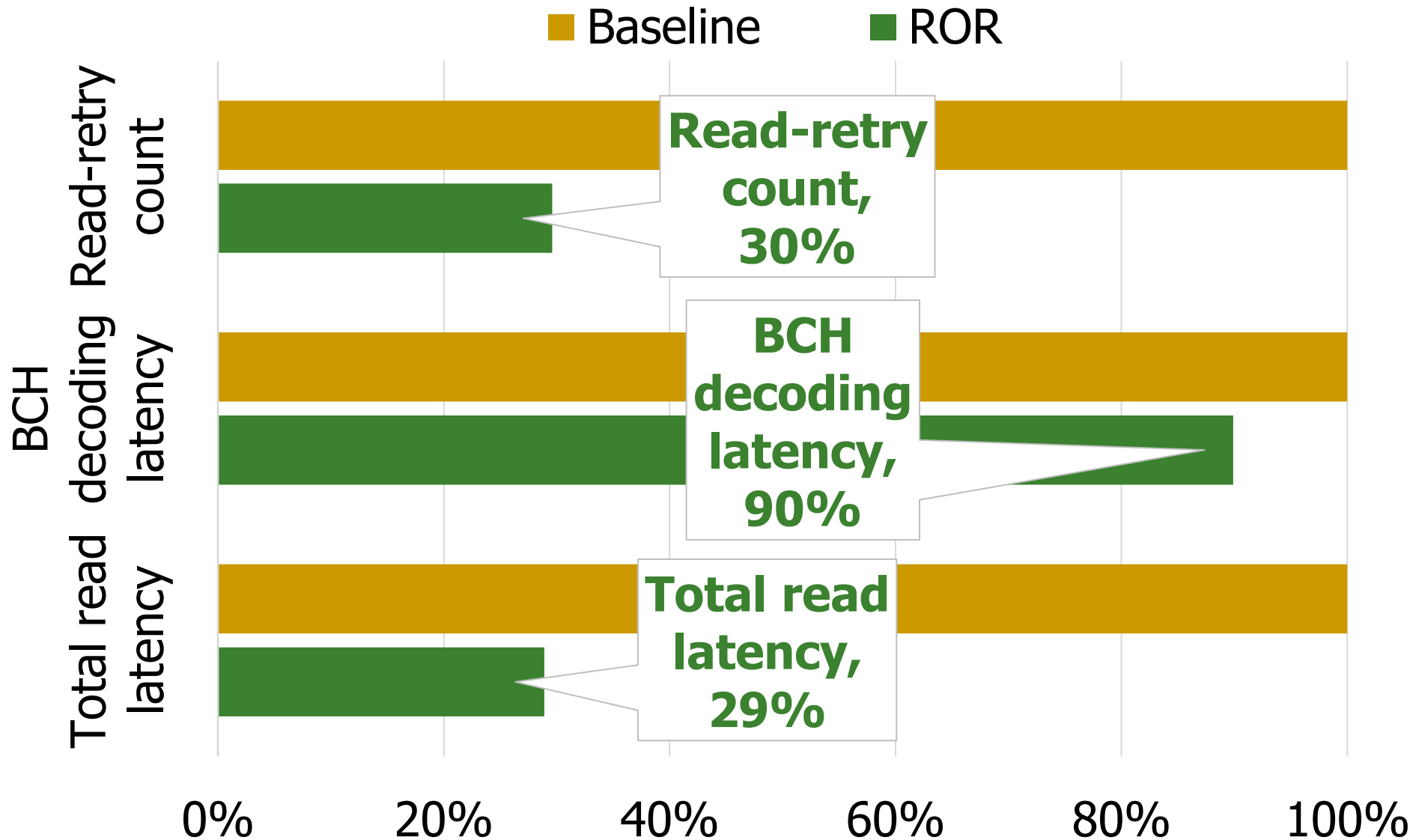
---

- Performed as normal read
- $V_{\text{pred}}$  already close to actual OPT
- Decrease  $V_{\text{ref}}$  if  $V_{\text{pred}}$  fails, and retry





# ROR result



# Retention optimized reading

---

Retention loss → longer read latency

Optimal read reference voltage (OPT)

→ Shortest read latency

→ Decreases gradually over time (retention)

→ Learn OPT periodically

→ Minimize read-retry & RBER

→ Shorter read latency

---

**Characterize**

retention loss in real NAND chip

**Optimize**

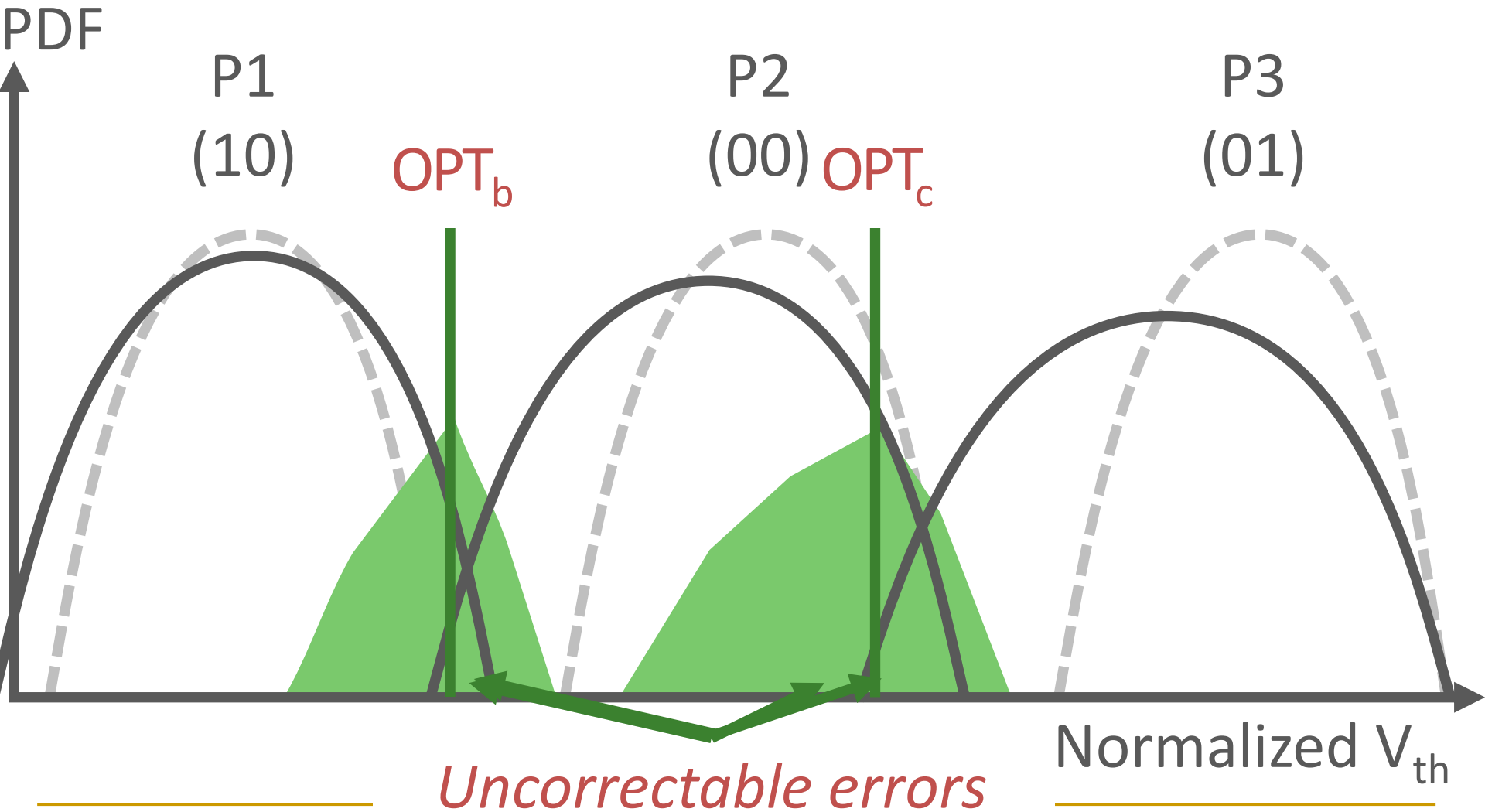
read performance for old data

**Recover**

old data after failure

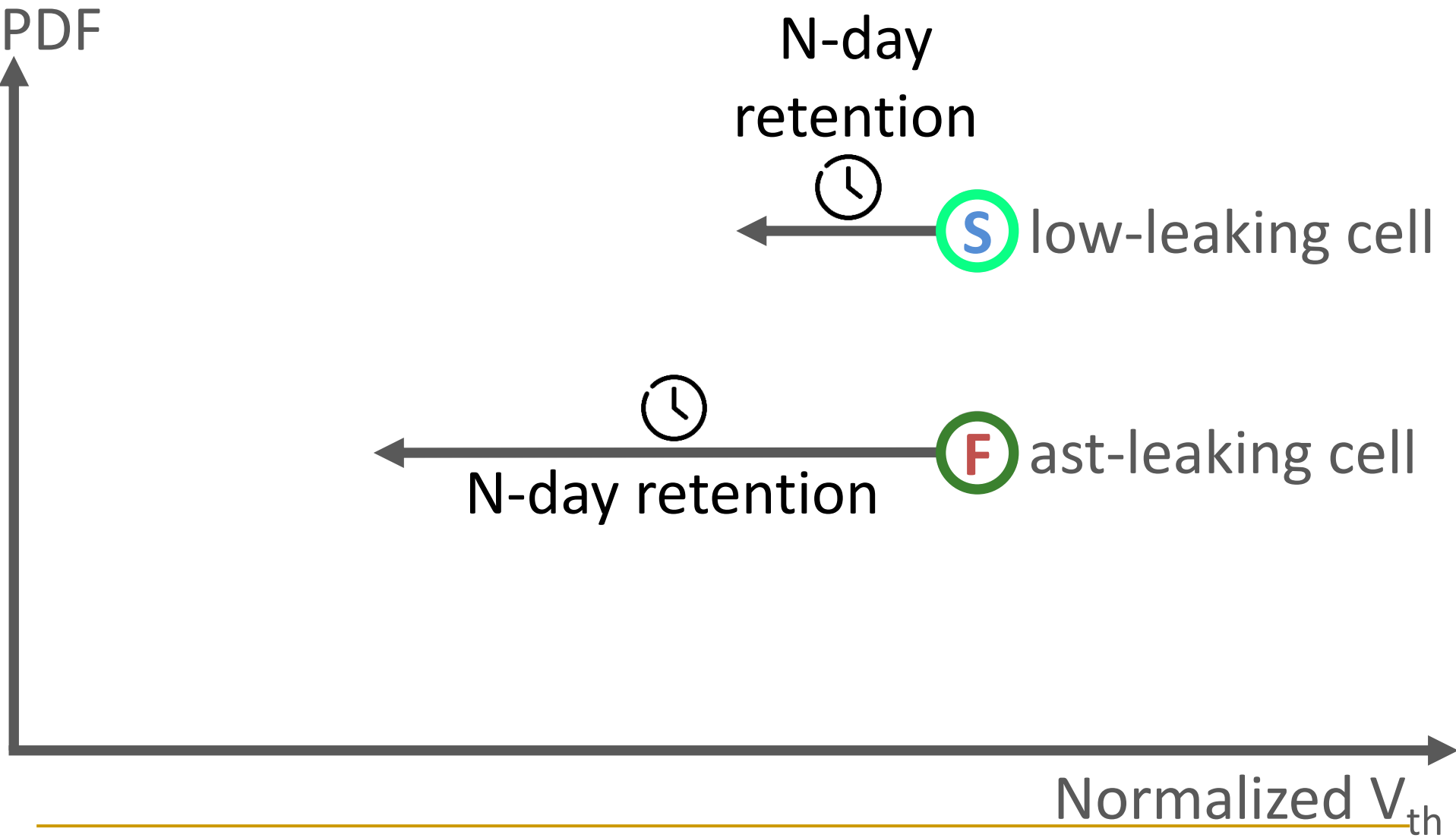
# Retention failure

Very old data



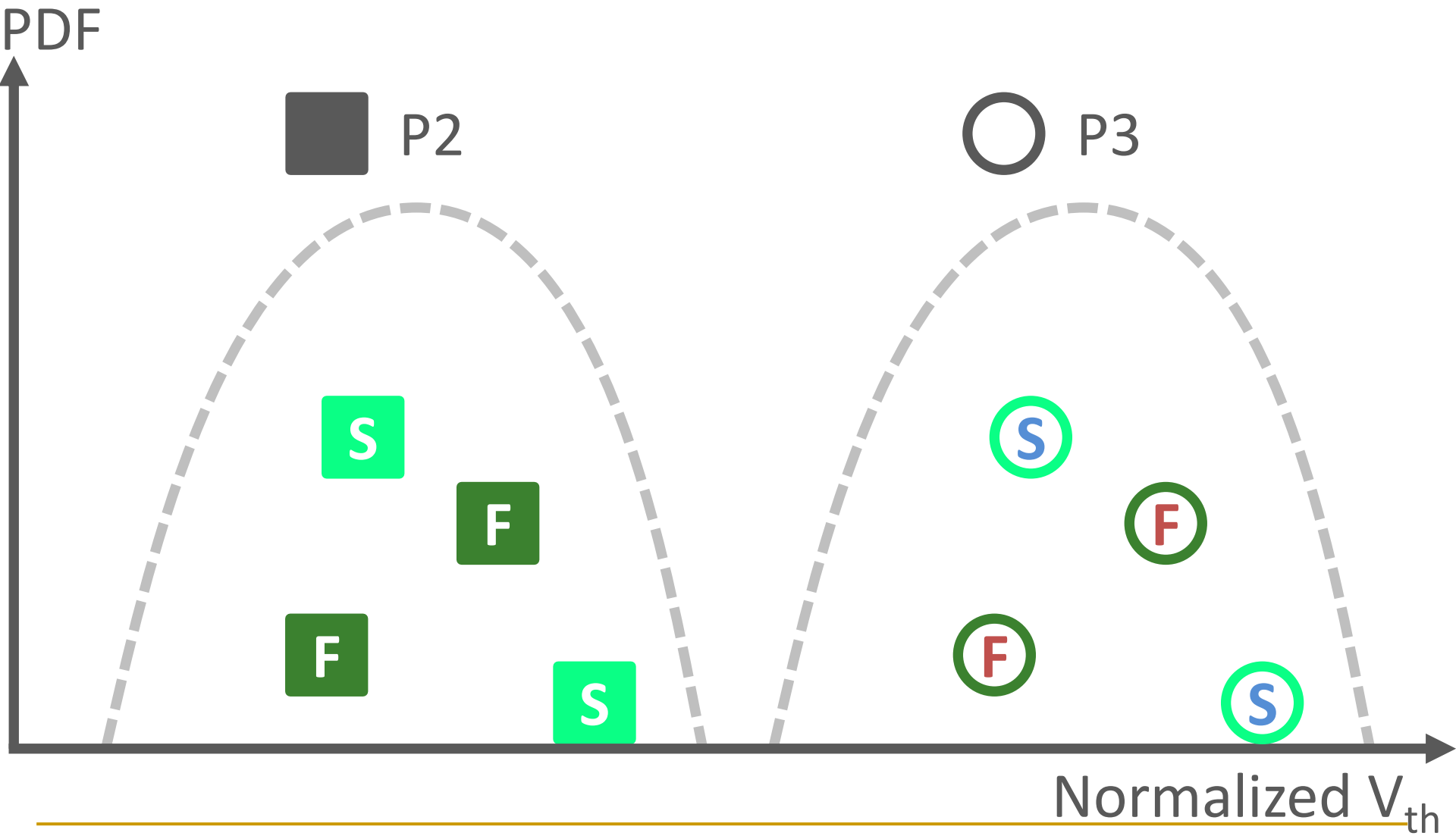
# Leakage speed variation

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# A simplified example

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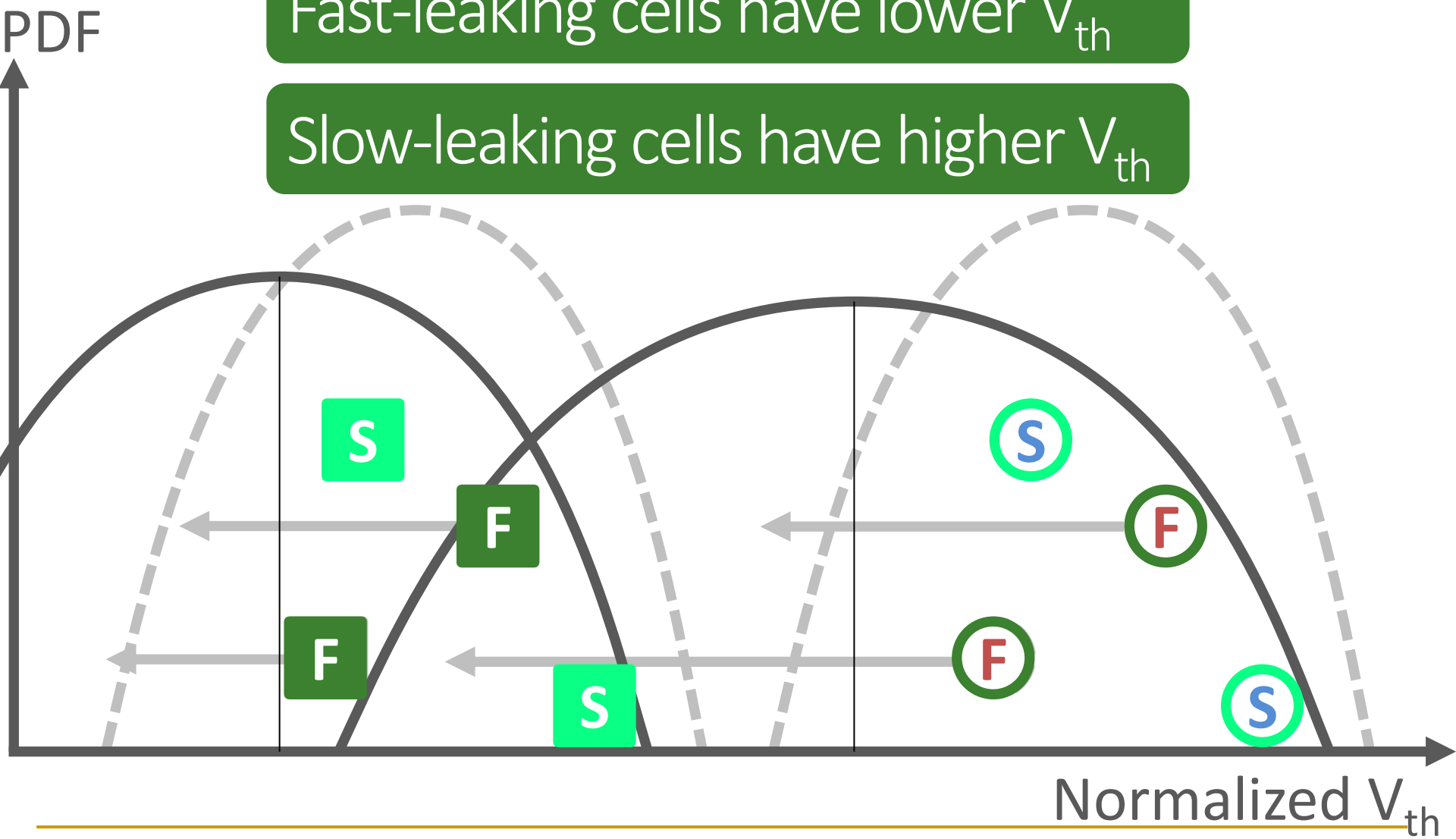


# Reading very old data

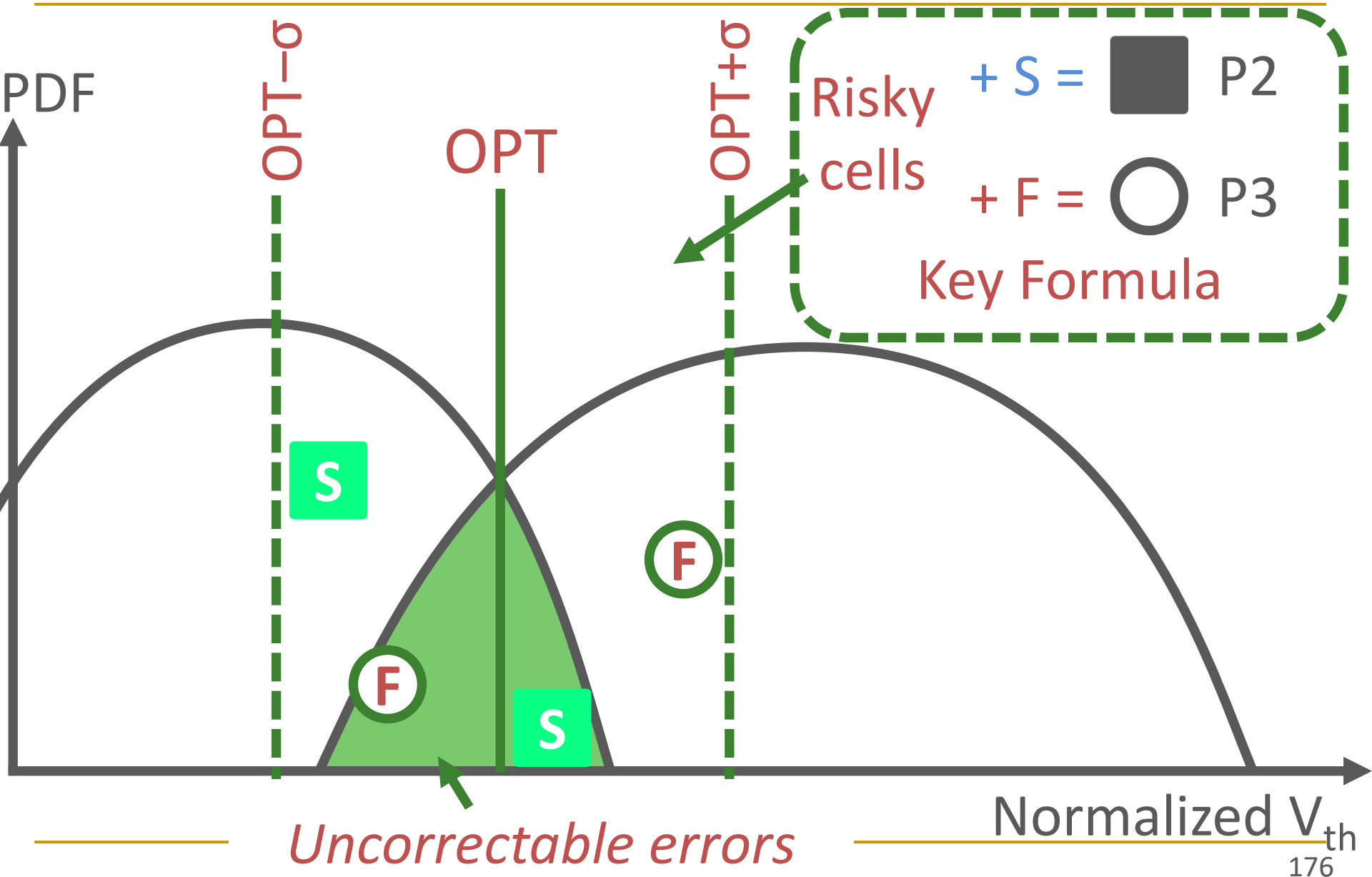
Very old data

Fast-leaking cells have lower  $V_{th}$

Slow-leaking cells have higher  $V_{th}$



# “Risky” cells





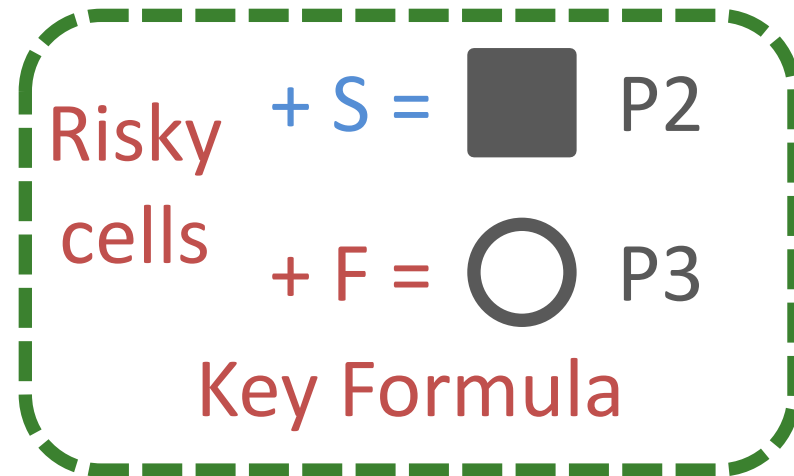
# Retention Failure Recovery (RFR)

---

Key idea: Guess original state of the cell from its leakage speed property

Three steps

1. Identify risky cells
2. Identify fast-/slow-leaking cells
3. Guess original states



# RFR Evaluation

---

*Program with  
random data*



*28 days*

*Detect failure,  
backup data*



*12 addt'l.  
days*

*Recover data*



- Expect to eliminate 50% of raw bit errors
- ECC can correct remaining errors

---

**Characterize**

retention loss in real NAND chip

**Optimize**

read performance for old data

**Recover**

old data after failure

# Conclusion

---

**Retention loss → Longer read latency**

**Retention optimized reading (ROR)**

→ Learns OPT periodically

→ 71% shorter read latency

**Retention failure recovery (RFR)**

→ Use leakage property to guess correct state

→ 50% error reduction before ECC correction

→ Recover data after failure

- Yu Cai, Yixin Luo, Erich F. Haratsch, Ken Mai, and Onur Mutlu,  
**"Data Retention in MLC NAND Flash Memory: Characterization, Optimization and Recovery"**  
*Proceedings of the 21st International Symposium on High-Performance Computer Architecture (HPCA)*, Bay Area, CA, February 2015.  
[[Slides \(pptx\)](#)] [[pdf](#)]

## Data Retention in MLC NAND Flash Memory: Characterization, Optimization, and Recovery

Yu Cai, Yixin Luo, Erich F. Haratsch\*, Ken Mai, Onur Mutlu  
Carnegie Mellon University, \*LSI Corporation

yucaicai@gmail.com, yixinluo@cs.cmu.edu, erich.haratsch@lsi.com, {kenmai, omutlu}@ece.cmu.edu

# Agenda

---

- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Main Characterization Results
  - Retention-Aware Error Management
  - Threshold Voltage and Program Interference Analysis
  - Read Reference Voltage Prediction
  - Neighbor-Assisted Error Correction
  - Read Disturb Error Handling
  - Retention Error Handling
  - Large Scale Field Analysis
  - 3D NAND Flash Memory Reliability
- Summary

# Large Scale Field Analysis of Flash Memory Errors

# SSD Error Analysis of Facebook Systems

---

- First large-scale field study of flash memory errors
- Justin Meza, Qiang Wu, Sanjeev Kumar, and Onur Mutlu,  
**"A Large-Scale Study of Flash Memory Errors in the Field"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (SIGMETRICS)*, Portland, OR, June 2015.  
[\[Slides \(pptx\) \(pdf\)\]](#) [\[Coverage at ZDNet\]](#) [\[Coverage on The Register\]](#) [\[Coverage on TechSpot\]](#) [\[Coverage on The Tech Report\]](#)

## A Large-Scale Study of Flash Memory Failures in the Field

Justin Meza  
Carnegie Mellon University  
meza@cmu.edu

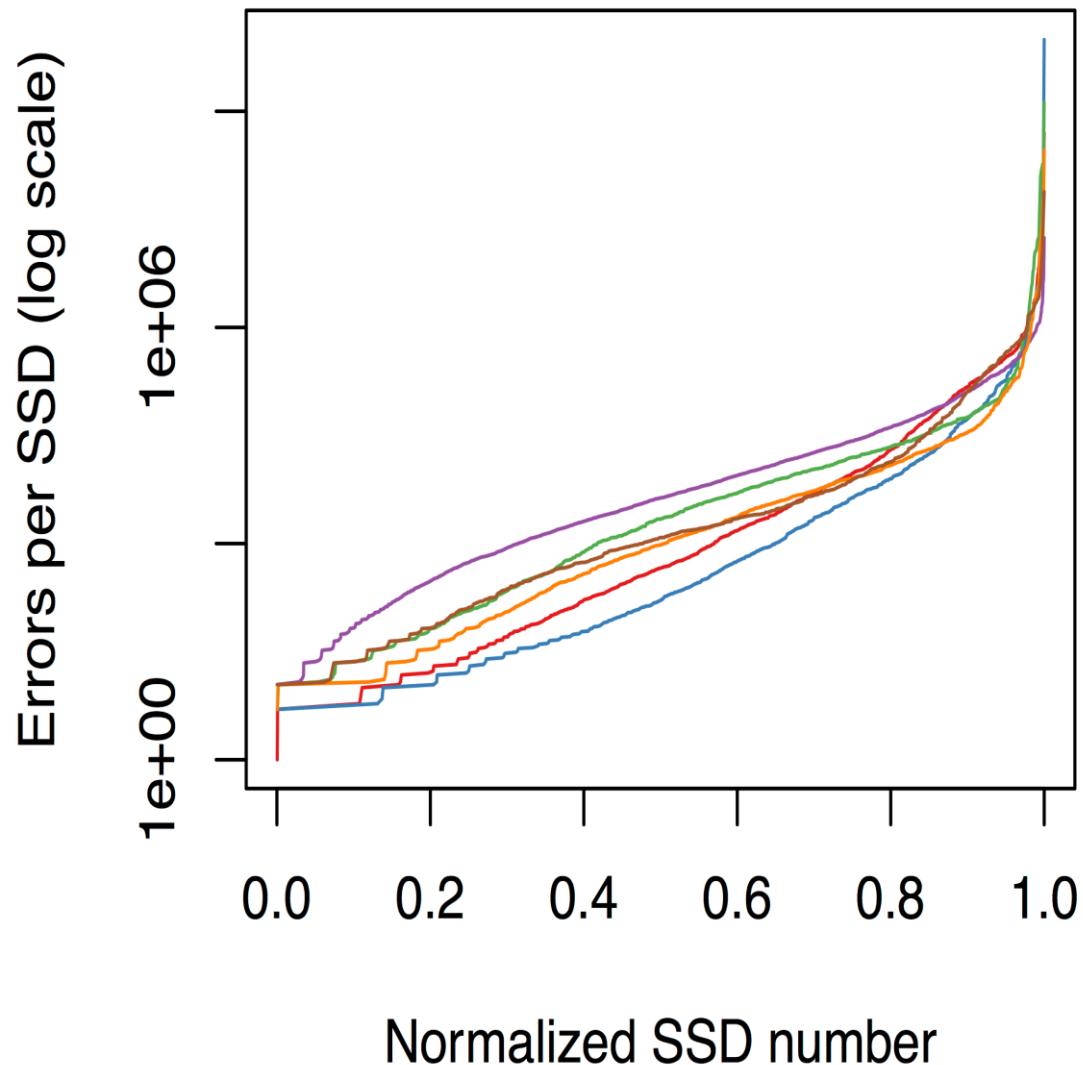
Qiang Wu  
Facebook, Inc.  
qw@fb.com

Sanjeev Kumar  
Facebook, Inc.  
skumar@fb.com

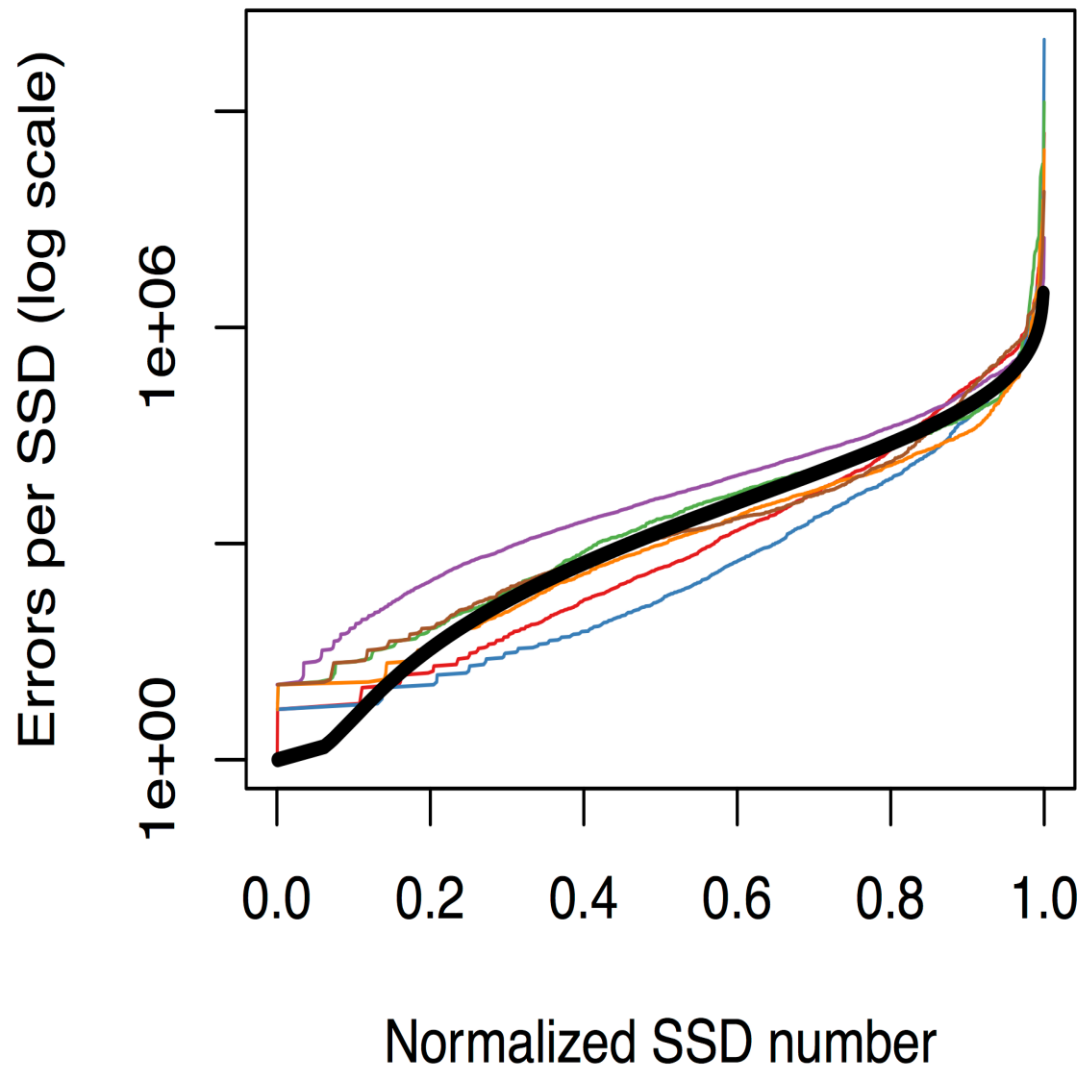
Onur Mutlu  
Carnegie Mellon University  
onur@cmu.edu



# A few SSDs cause most errors



# A few SSDs cause most errors



# Summary

SSD lifecycle

*Access pattern  
dependence*



*Read  
disturbance*

Temperature

# Summary

SSD lifecycle



***Early detection*** lifecycle period  
distinct from hard disk drive  
lifecycle.

Temperature

# SSD lifecycle

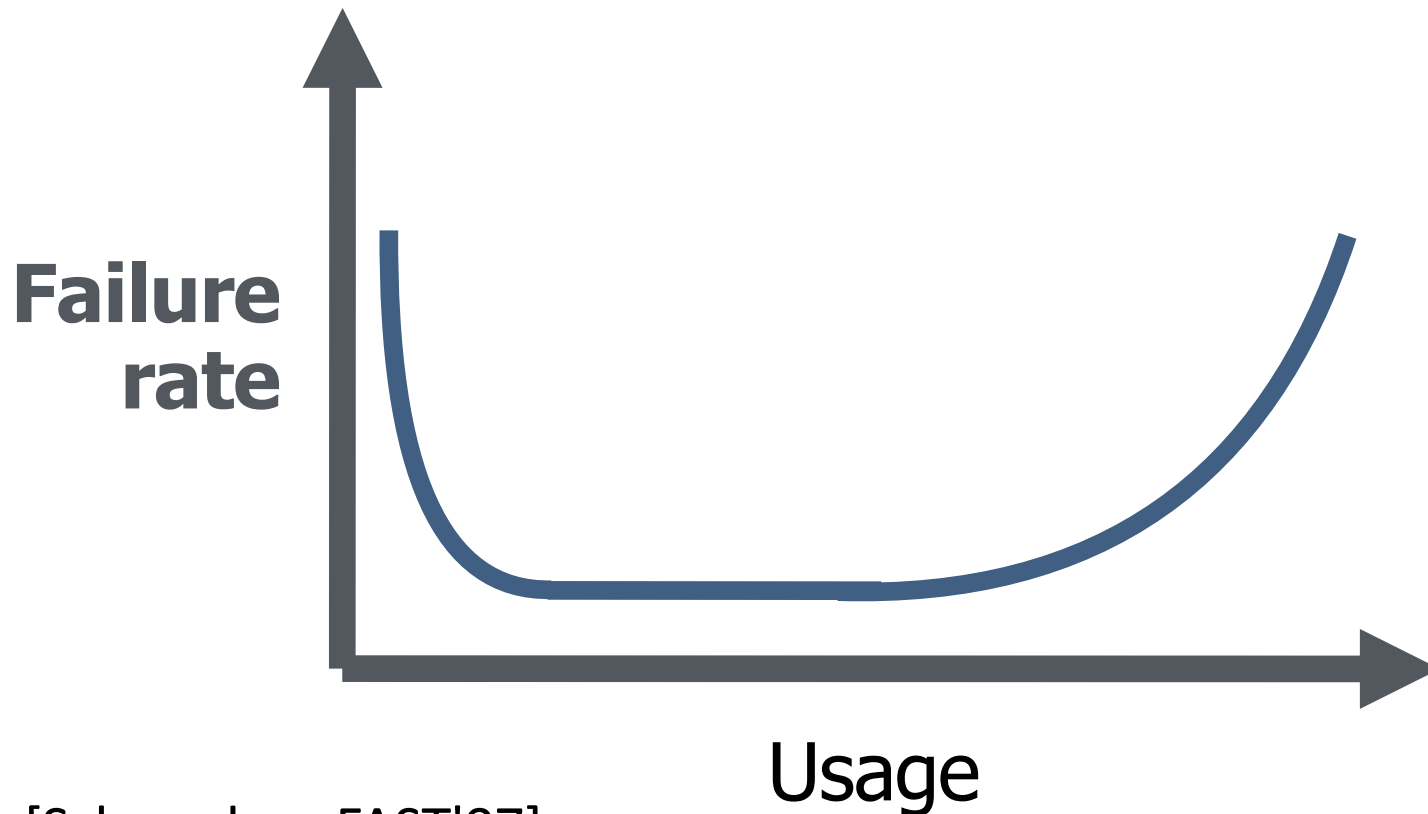
*Access pattern  
dependence*

New reliability  
trends

*Read  
disturbance*

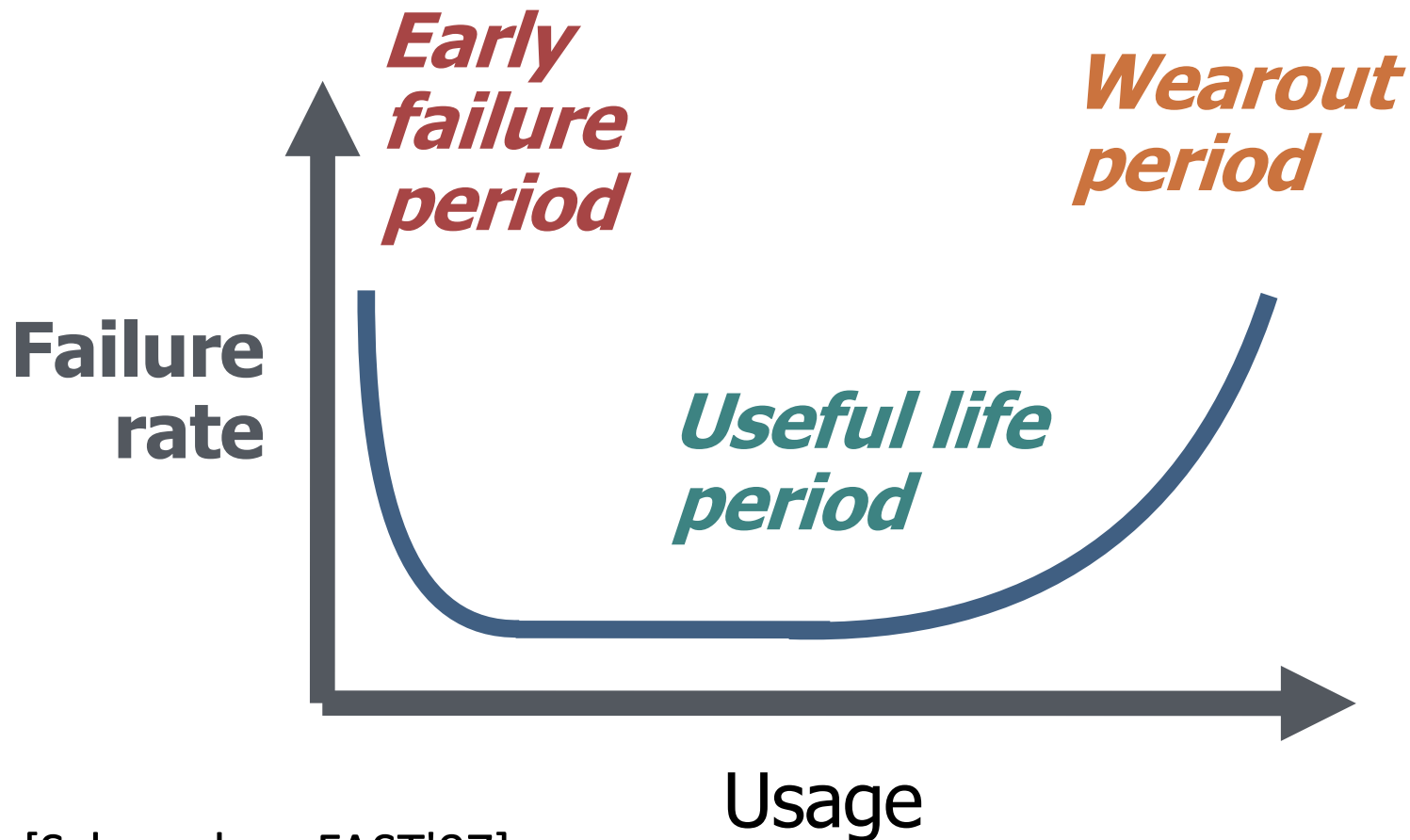
Temperature

# Storage lifecycle background: the bathtub curve for disk drives



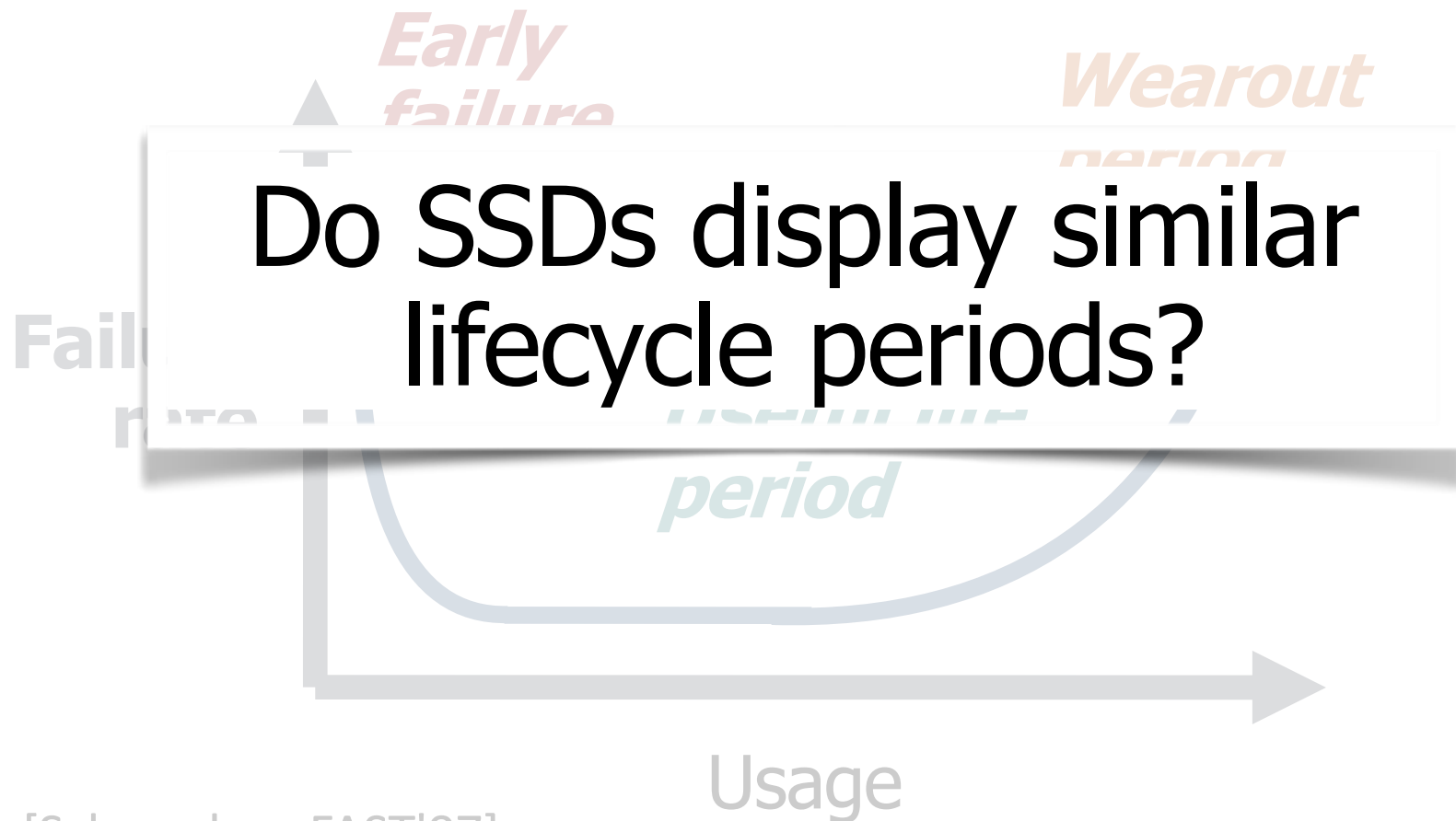
[Schroeder+,FAST'07]

# Storage lifecycle background: the bathtub curve for disk drives



[Schroeder+,FAST'07]

Storage lifecycle background:  
the bathtub curve for disk drives

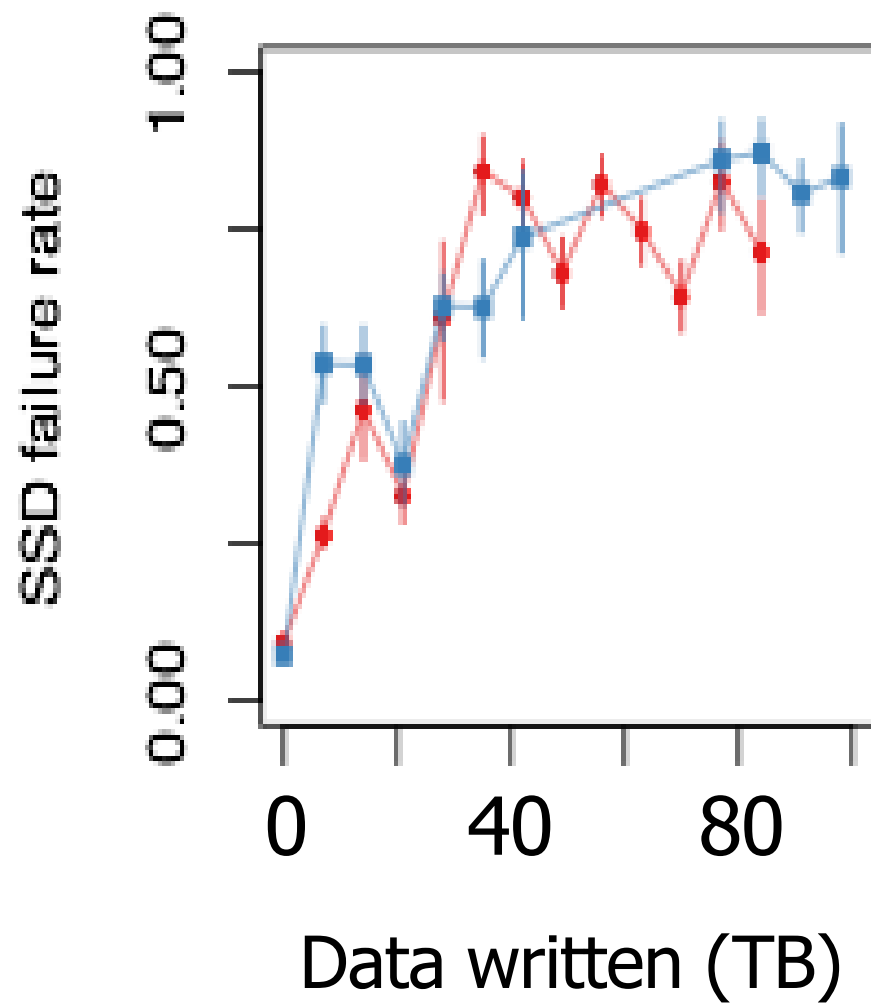




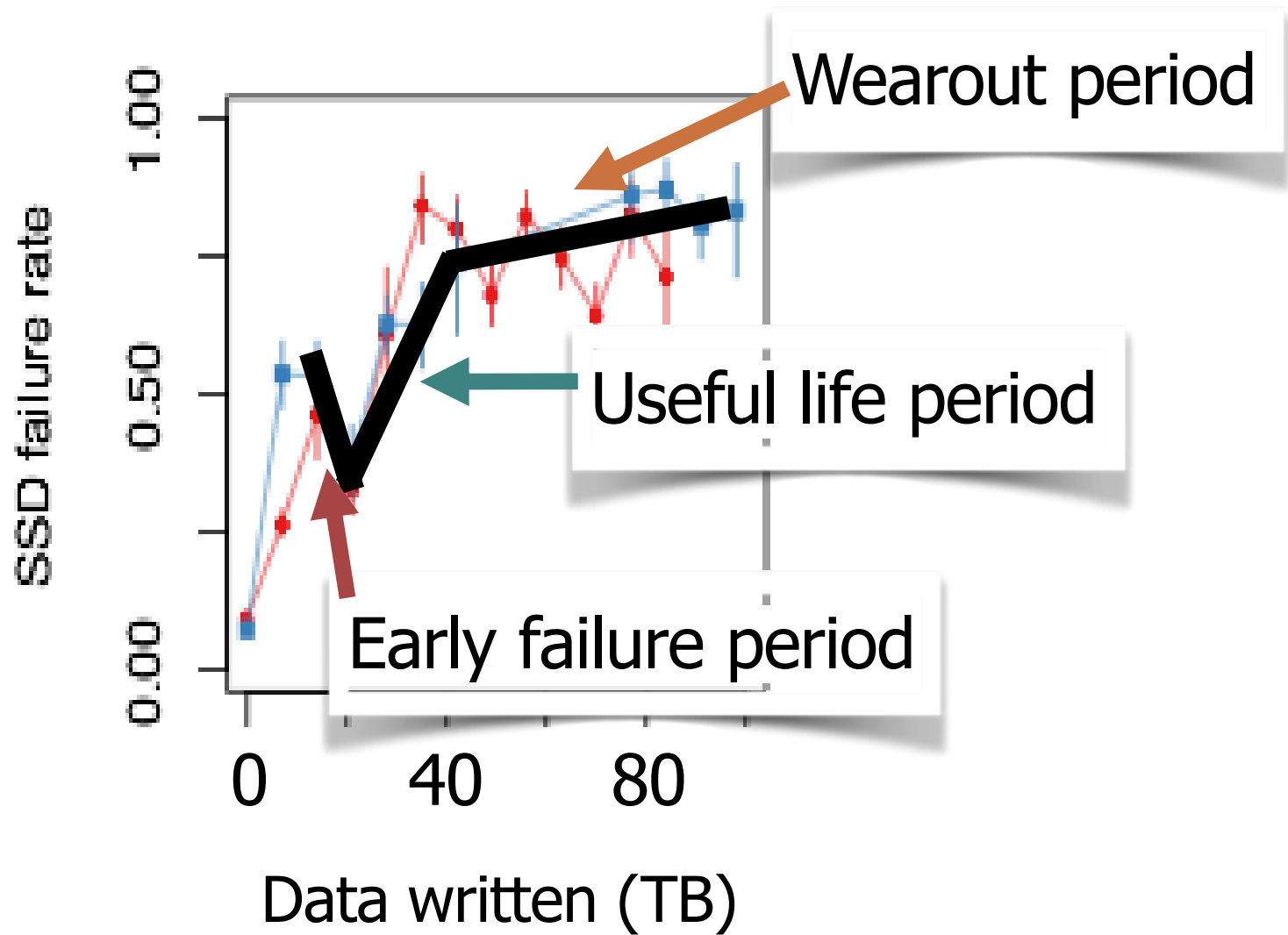
Use data written to flash  
to examine SSD lifecycle

(time-independent utilization metric)

720GB, 1 SSD    720GB, 2 SSDs



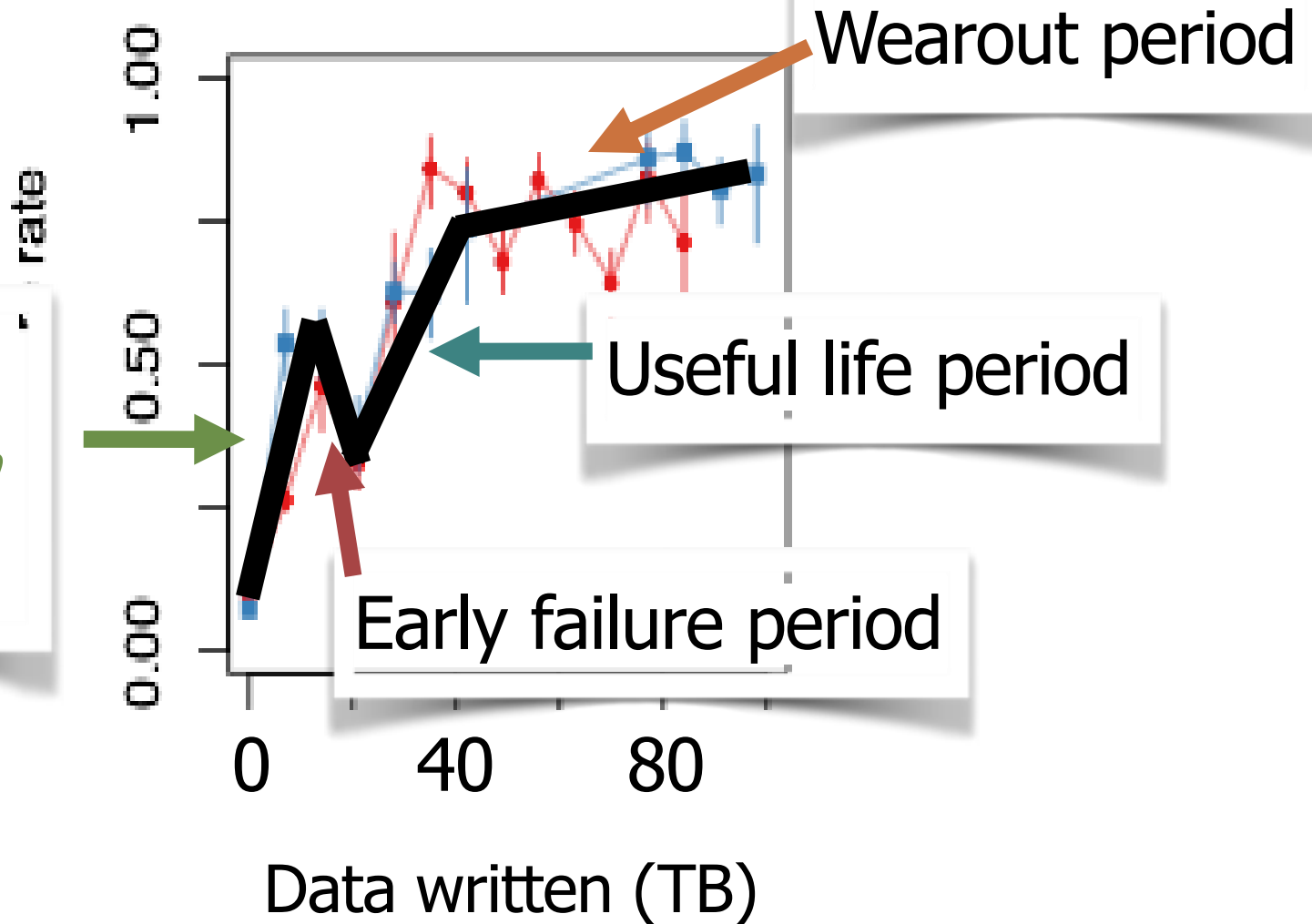
720GB, 1 SSD    720GB, 2 SSDs



720GB, 1 SSD

720GB, 2 SSDs

*Early  
detection  
period*



# SSD lifecycle



The diagram consists of a blue pyramid pointing downwards towards a white rectangular box. From the bottom of this box, a red pyramid points downwards towards the word 'Temperature'.

***Early detection*** lifecycle period  
distinct from hard disk drive  
lifecycle.

Temperature

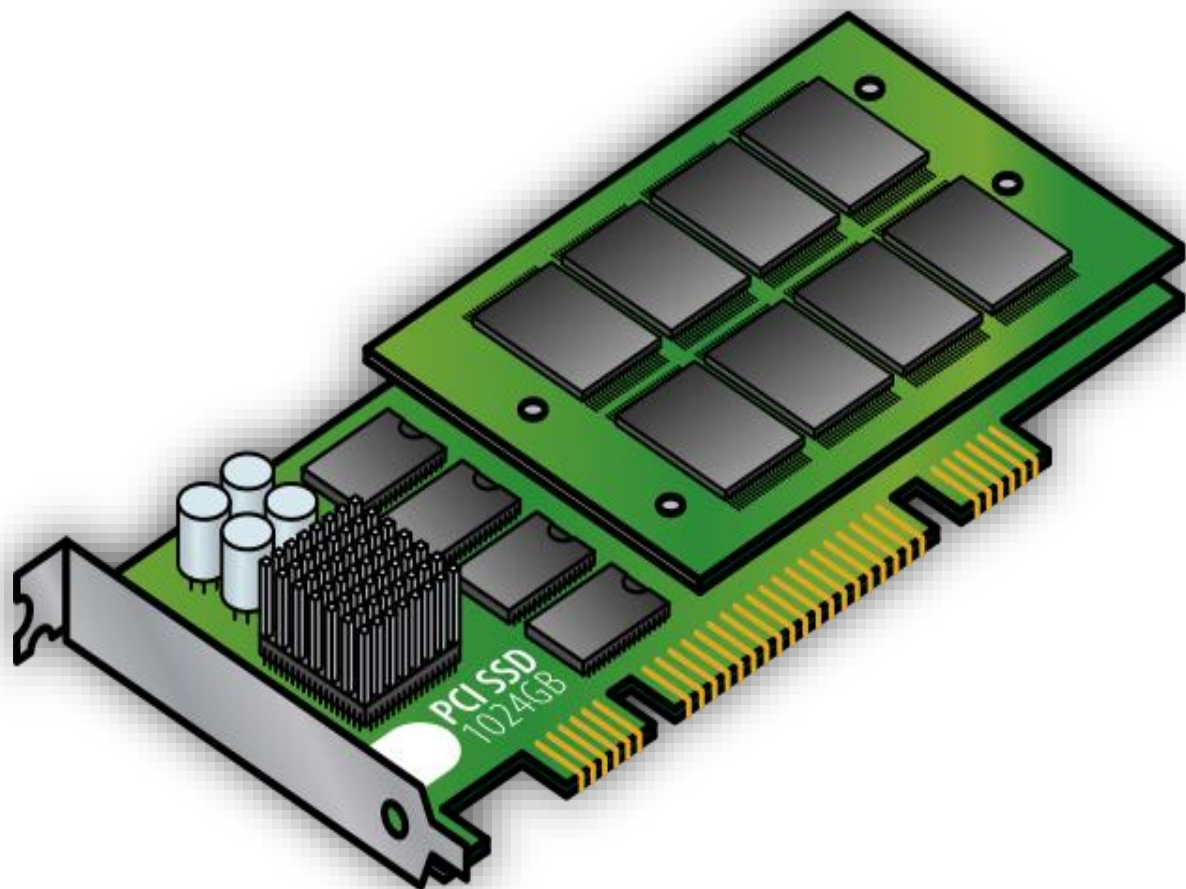
SSD lifecycle

*Access pattern  
dependence*

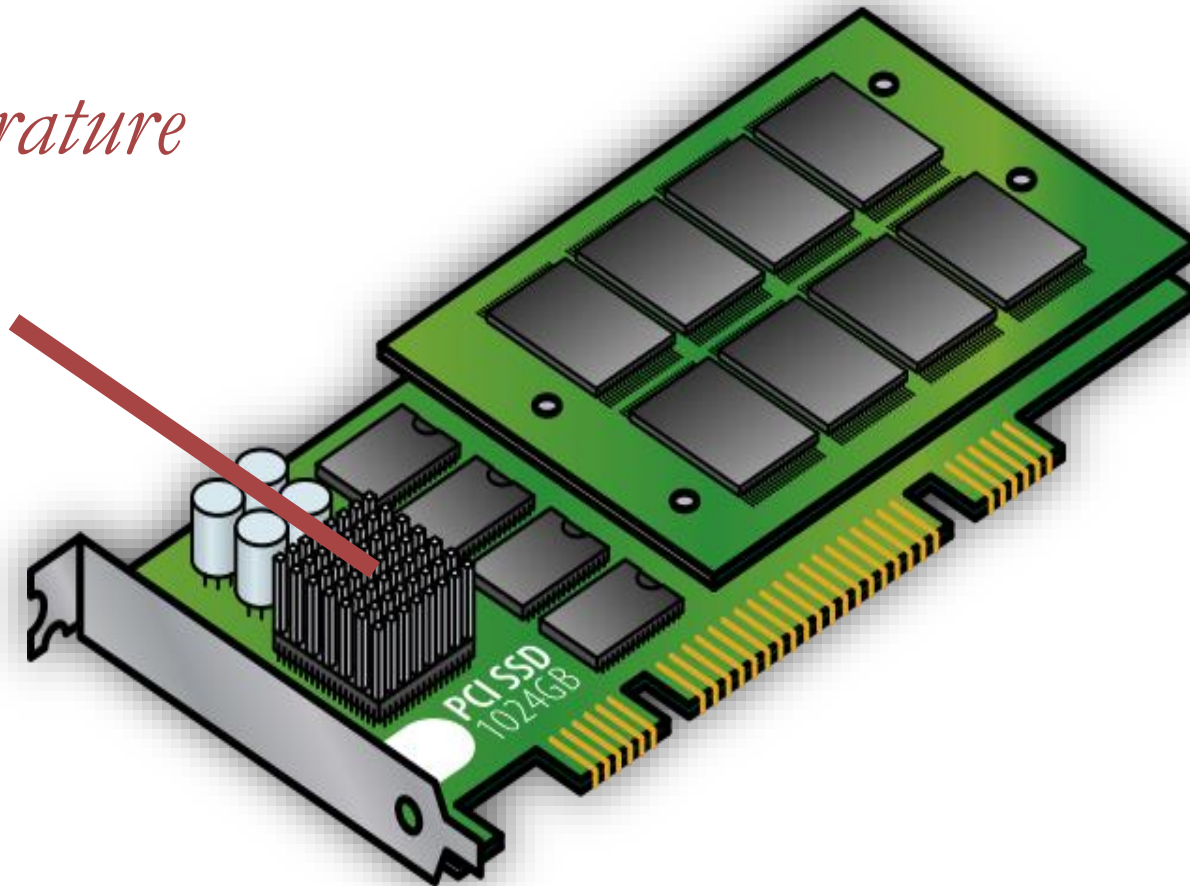
New reliability  
trends

*Read  
disturbance*

Temperature

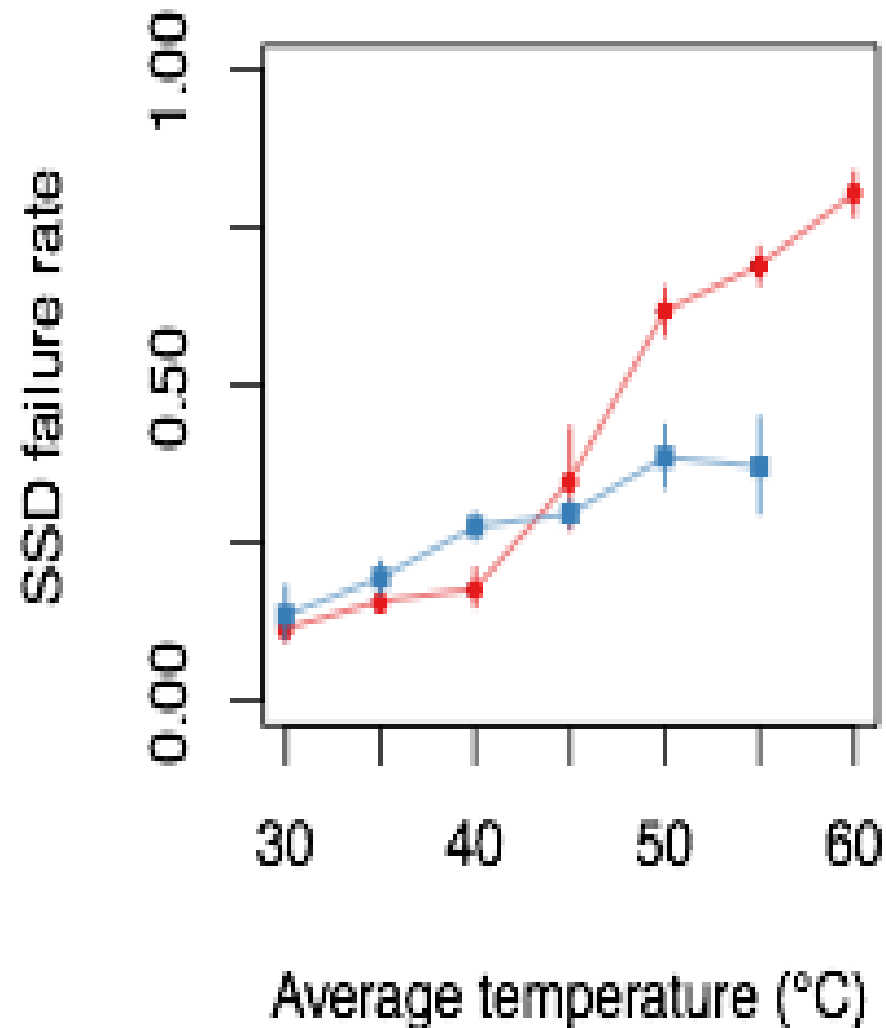


*Temperature  
sensor*

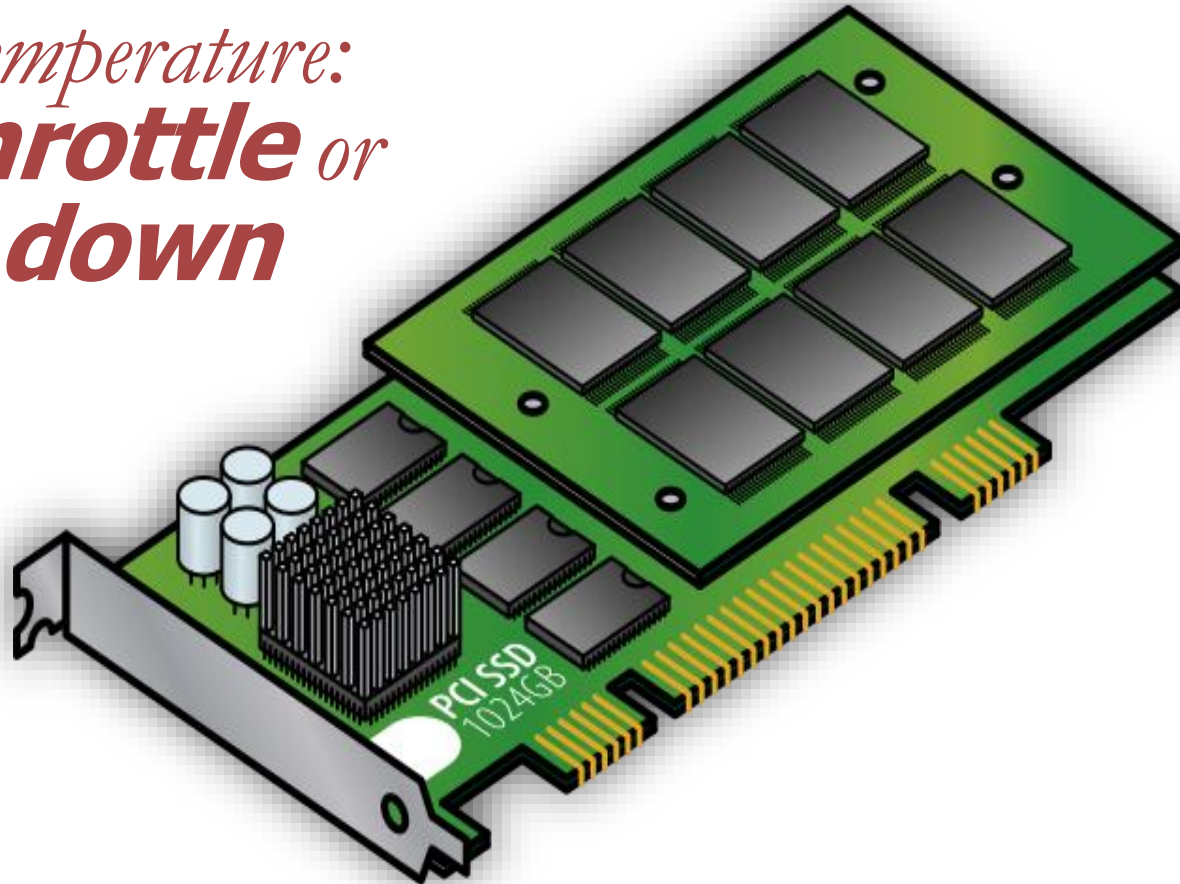




720GB, 1 SSD    720GB, 2 SSDs

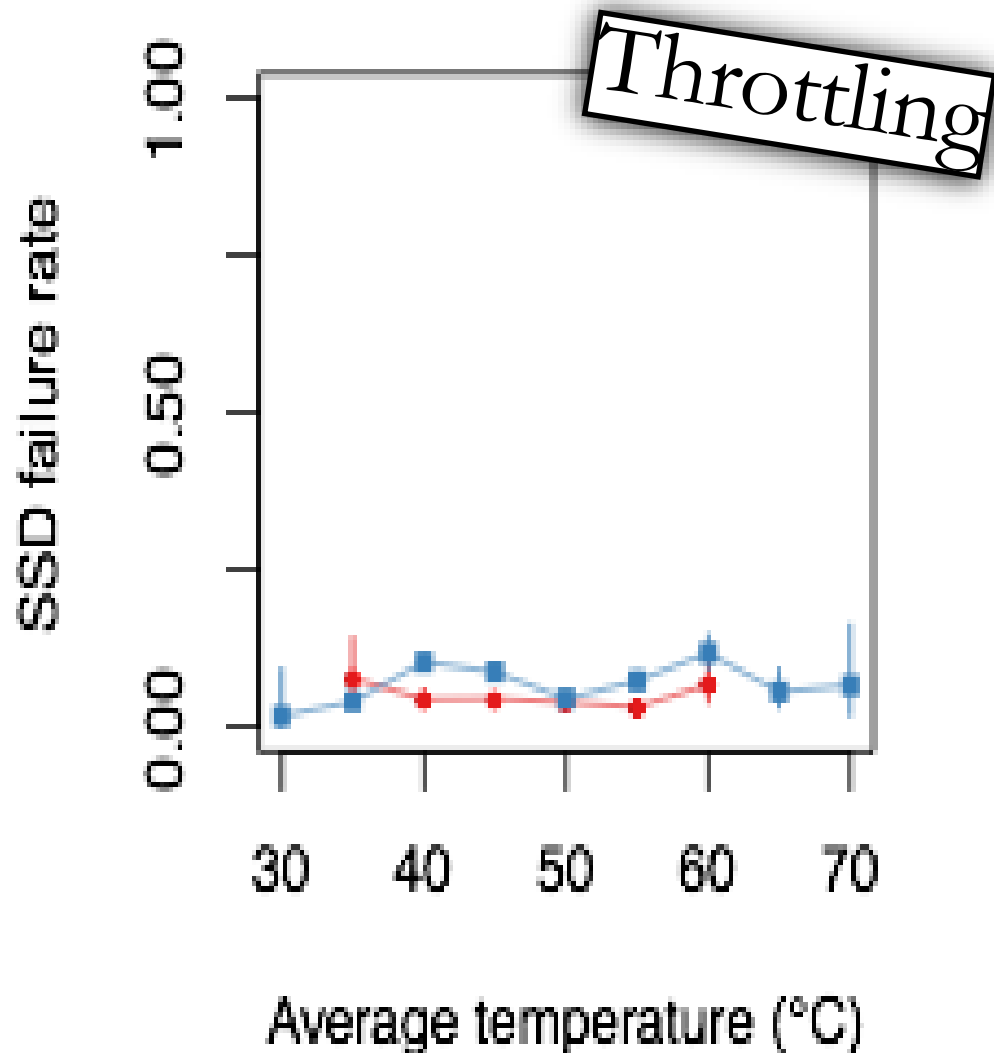


High temperature:  
may **throttle** or  
**shut down**



1.2TB, 1 SSD

3.2TB, 1 SSD



SSD lifecycle

***Throttling SSD usage*** helps  
mitigate temperature-induced  
errors.

Temperature

# Summary

SSD lifecycle

We ***do not*** observe the effects of ***read disturbance*** errors in the field.

*Read disturbance*

Temperature

# Summary

SSD lifecycle



The diagram features a central white rectangular box with a subtle drop shadow. Above the box is a red upward-pointing triangle, and below it is a blue downward-pointing triangle. The text 'SSD lifecycle' is positioned above the red triangle, and 'Temperature' is positioned below the blue triangle. Inside the white box, the text '**Throttling SSD usage** helps mitigate temperature-induced errors.' is displayed in a dark blue font. The word 'Throttling' is in bold and italicized, while 'SSD usage' is in bold. The rest of the text is in a standard weight.

**Throttling SSD usage** helps mitigate temperature-induced errors.

Temperature

# Summary

SSD lifecycle

*Access pattern  
dependence*

We quantify the effects of the ***page cache*** and ***write amplification*** in the field.

Temperature

# Large-Scale SSD Error Analysis [SIGMETRICS'15]

---

- First large-scale field study of flash memory errors
- Justin Meza, Qiang Wu, Sanjeev Kumar, and Onur Mutlu,  
**"A Large-Scale Study of Flash Memory Errors in the Field"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (SIGMETRICS)*, Portland, OR, June 2015.  
[[Slides \(pptx\)](#)] [[pdf](#)] [[Coverage at ZDNet](#)] [[Coverage on The Register](#)]  
[[Coverage on TechSpot](#)] [[Coverage on The Tech Report](#)]

## A Large-Scale Study of Flash Memory Failures in the Field

Justin Meza  
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Facebook, Inc.  
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Sanjeev Kumar  
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skumar@fb.com

Onur Mutlu  
Carnegie Mellon University  
onur@cmu.edu



# Other Works on NAND Flash Memory Modeling & Issues

# Flash Memory Programming Vulnerabilities

---

- Yu Cai, Saugata Ghose, Yixin Luo, Ken Mai, Onur Mutlu, and Erich F. Haratsch,  
**"Vulnerabilities in MLC NAND Flash Memory Programming: Experimental Analysis, Exploits, and Mitigation Techniques"**  
*Proceedings of the 23rd International Symposium on High-Performance Computer Architecture (HPCA) Industrial Session*, Austin, TX, USA, February 2017.  
[[Slides \(pptx\)](#)] [[pdf](#)] [[Lightning Session Slides \(pptx\)](#)] [[pdf](#)]

## Vulnerabilities in MLC NAND Flash Memory Programming: Experimental Analysis, Exploits, and Mitigation Techniques

Yu Cai<sup>†</sup>      Saugata Ghose<sup>†</sup>      Yixin Luo<sup>‡‡</sup>      Ken Mai<sup>†</sup>      Onur Mutlu<sup>§†</sup>      Erich F. Haratsch<sup>‡</sup>  
<sup>†</sup>*Carnegie Mellon University*      <sup>‡</sup>*Seagate Technology*      <sup>§</sup>*ETH Zürich*

# Accurate and Online Channel Modeling

---

- Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, and Onur Mutlu,  
**"Enabling Accurate and Practical Online Flash Channel Modeling  
for Modern MLC NAND Flash Memory"**  
*to appear in IEEE Journal on Selected Areas in Communications (JSAC),  
2016.*

## Enabling Accurate and Practical Online Flash Channel Modeling for Modern MLC NAND Flash Memory

Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, Onur Mutlu

# Agenda

---

- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Main Characterization Results
  - Retention-Aware Error Management
  - Threshold Voltage and Program Interference Analysis
  - Read Reference Voltage Prediction
  - Neighbor-Assisted Error Correction
  - Read Disturb Error Handling
  - Retention Error Handling
  - Large Scale Field Analysis
  - 3D NAND Flash Memory Reliability
- Summary

# 3D NAND Flash Memory

# 3D NAND Flash Reliability I [HPCA'18]

---

- Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, and Onur Mutlu, **"HeatWatch: Improving 3D NAND Flash Memory Device Reliability by Exploiting Self-Recovery and Temperature-Awareness"**

*Proceedings of the 24th International Symposium on High-Performance Computer Architecture (HPCA)*, Vienna, Austria, February 2018.

[[Lightning Talk Video](#)]

[[Slides \(pptx\)](#)] [[pdf](#)] [[Lightning Session Slides \(pptx\)](#)] [[pdf](#)]

## HeatWatch: Improving 3D NAND Flash Memory Device Reliability by Exploiting Self-Recovery and Temperature Awareness

Yixin Luo<sup>†</sup>      Saugata Ghose<sup>†</sup>      Yu Cai<sup>‡</sup>      Erich F. Haratsch<sup>‡</sup>      Onur Mutlu<sup>§†</sup>  
<sup>†</sup>*Carnegie Mellon University*      <sup>‡</sup>*Seagate Technology*      <sup>§</sup>*ETH Zürich*

# 3D NAND Flash Reliability II [SIGMETRICS'18]

---

- Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, and Onur Mutlu,  
**"Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (**SIGMETRICS**), Irvine, CA, USA, June 2018.*  
[[Abstract](#)]

## Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation

Yixin Luo<sup>†</sup>

Saugata Ghose<sup>†</sup>

Yu Cai<sup>†</sup>

Erich F. Haratsch<sup>‡</sup>

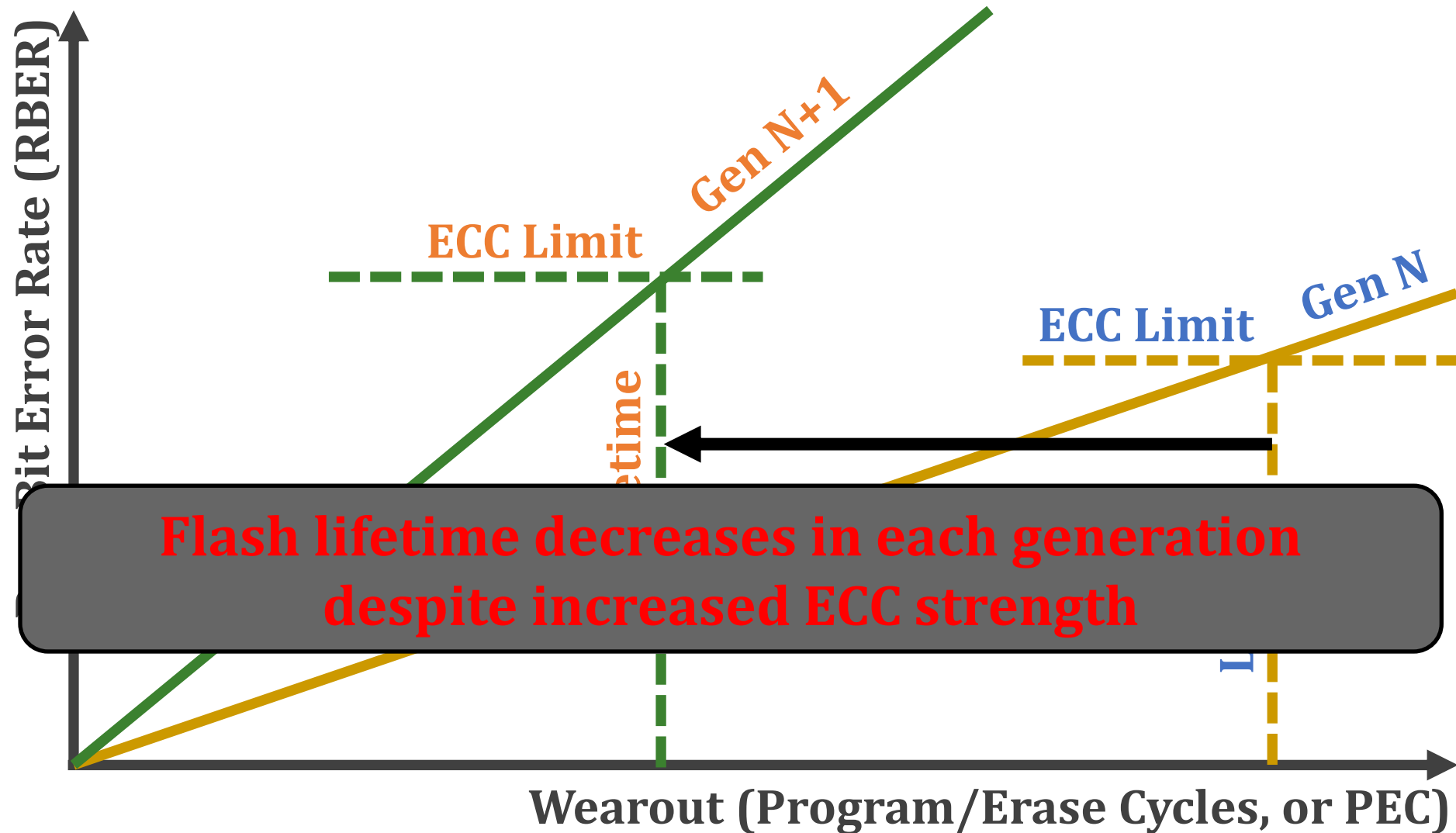
Onur Mutlu<sup>§†</sup>

<sup>†</sup>Carnegie Mellon University

<sup>‡</sup>Seagate Technology

<sup>§</sup>ETH Zürich

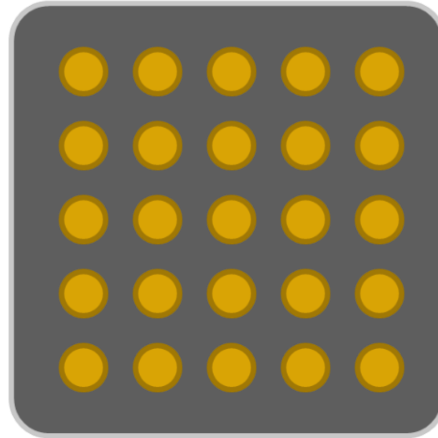
# NAND Flash Memory Lifetime Problem



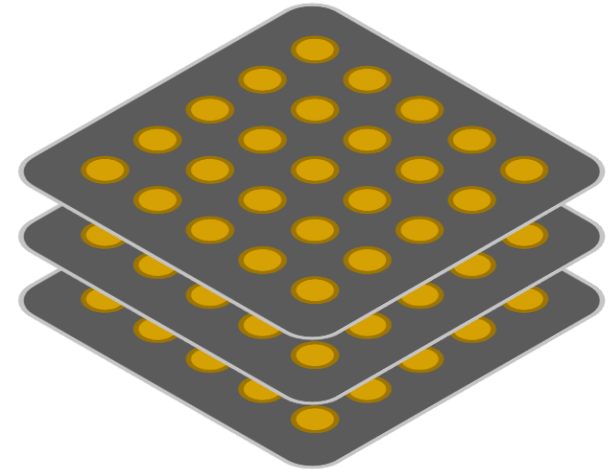


# Planar vs. 3D NAND Flash Memory

---



**Planar NAND  
Flash Memory**



**3D NAND  
Flash Memory**

## **Scaling**

Reduce flash cell size,  
Reduce distance b/w cells

Increase # of layers

## **Reliability**

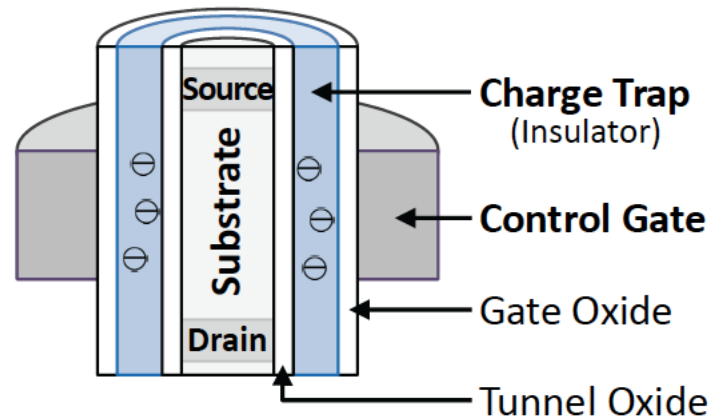
Scaling hurts reliability

**Not well studied!**

# Charge Trap Based 3D Flash Cell

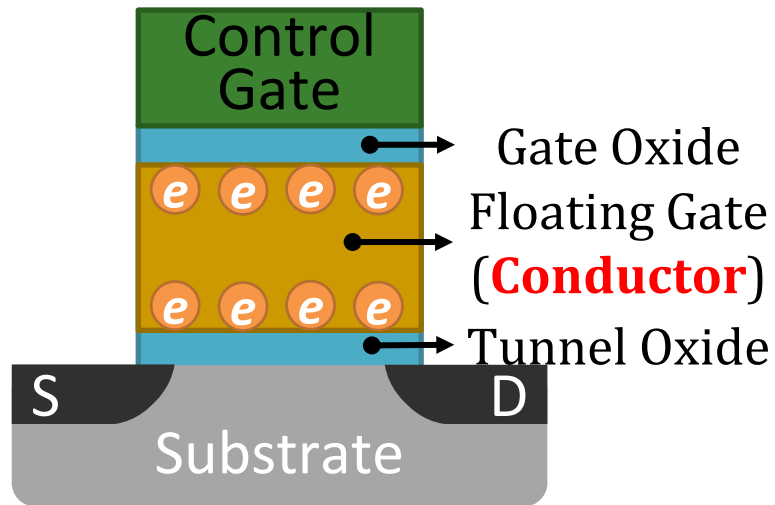
---

- Cross-section of a charge trap transistor

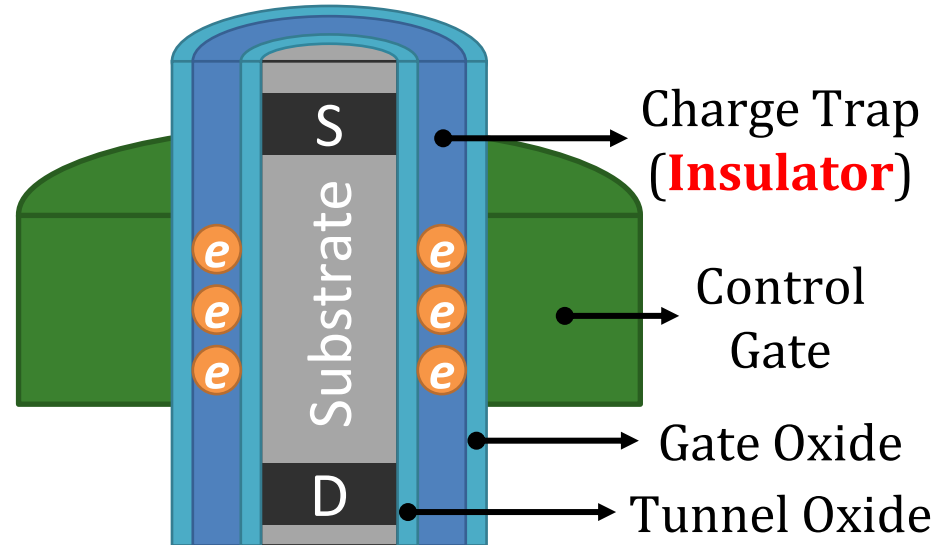


# 2D vs. 3D Flash Cell Design

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2D Floating-Gate Cell



3D Charge-Trap Cell

# 3D NAND Flash Memory Organization

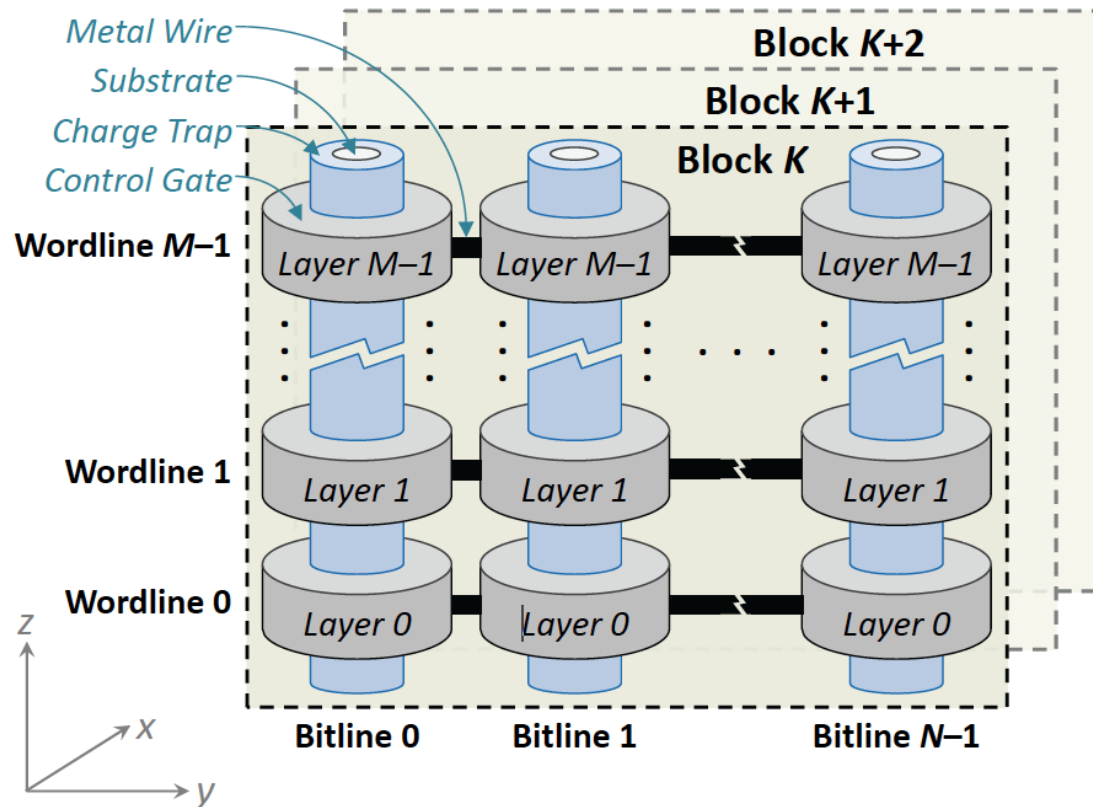


Fig. 43. Organization of flash cells in an  $M$ -layer 3D charge trap NAND flash memory chip, where each block consists of  $M$  wordlines and  $N$  bitlines.

# More Background and State-of-the-Art

---

- Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu, **"Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery"**  
*Invited Book Chapter in Inside Solid State Drives*, 2018.  
[Preliminary arxiv.org version]

## Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery

YU CAI, SAUGATA GHOSE

Carnegie Mellon University

ERICH F. HARATSCH

Seagate Technology

YIXIN LUO

Carnegie Mellon University

ONUR MUTLU

ETH Zürich and Carnegie Mellon University

# 3D vs. Planar NAND Errors: Comparison

---

Table 4. Changes in behavior of different types of errors in 3D NAND flash memory, compared to planar (i.e., two-dimensional) NAND flash memory. See Section 6.2 for a detailed discussion.

Error Type	Change in 3D vs. Planar
<b>P/E Cycling</b> (Section 3.1)	3D is <i>less susceptible</i> , due to current use of charge trap transistors for flash cells
<b>Program</b> (Section 3.2)	3D is <i>less susceptible for now</i> , due to use of one-shot programming (see Section 2.4)
<b>Cell-to-Cell Interference</b> (Section 3.3)	3D is <i>less susceptible for now</i> , due to larger manufacturing process technology
<b>Data Retention</b> (Section 3.4)	3D is <i>more susceptible</i> , due to early retention loss
<b>Read Disturb</b> (Section 3.5)	3D is <i>less susceptible for now</i> , due to larger manufacturing process technology

# Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation

Yixin Luo   Saugata Ghose   Yu Cai   Erich F. Haratsch  
Onur Mutlu

Carnegie Mellon



**ETH** Zürich

**SAFARI**



# Executive Summary

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- Problem: 3D NAND error characteristics are not well studied
- Goal: *Understand & mitigate* 3D NAND errors to improve lifetime
- Contribution 1: Characterize real 3D NAND flash chips
  - *Process variation: 21 × error rate difference across layers*
  - *Early retention loss: Error rate increases by 10 × after 3 hours*



# Agenda

---

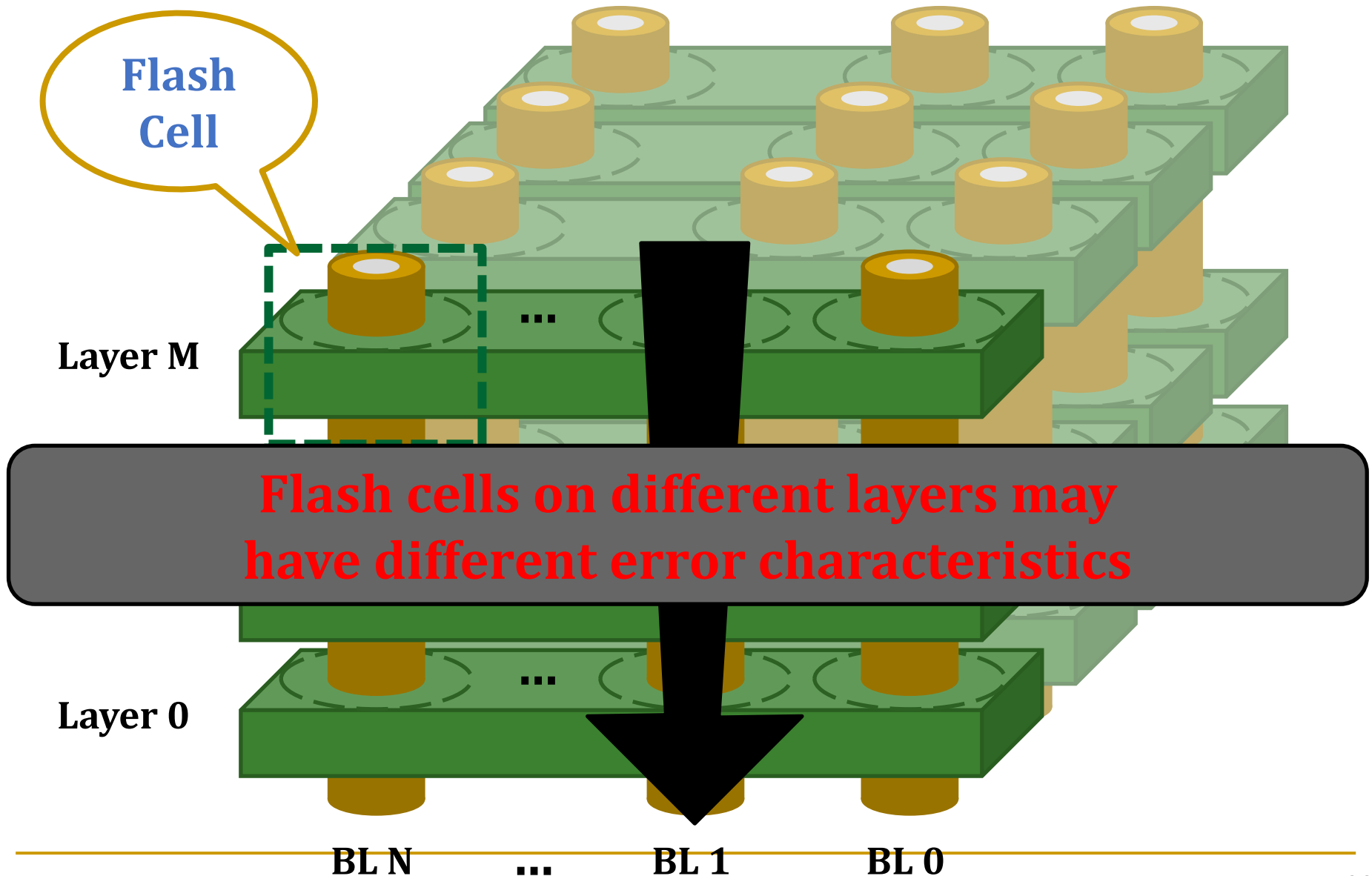
- Background & Introduction
- Contribution 1: Characterize real 3D NAND flash chips
- Contribution 2: Model RBER and threshold voltage
- Contribution 3: Mitigate 3D NAND flash

# Agenda

---

- Background & Introduction
- Contribution 1: Characterize real 3D NAND flash chips
  - Process variation
  - Early retention loss
  - Retention interference
- Contribution 2: Model RBER and threshold

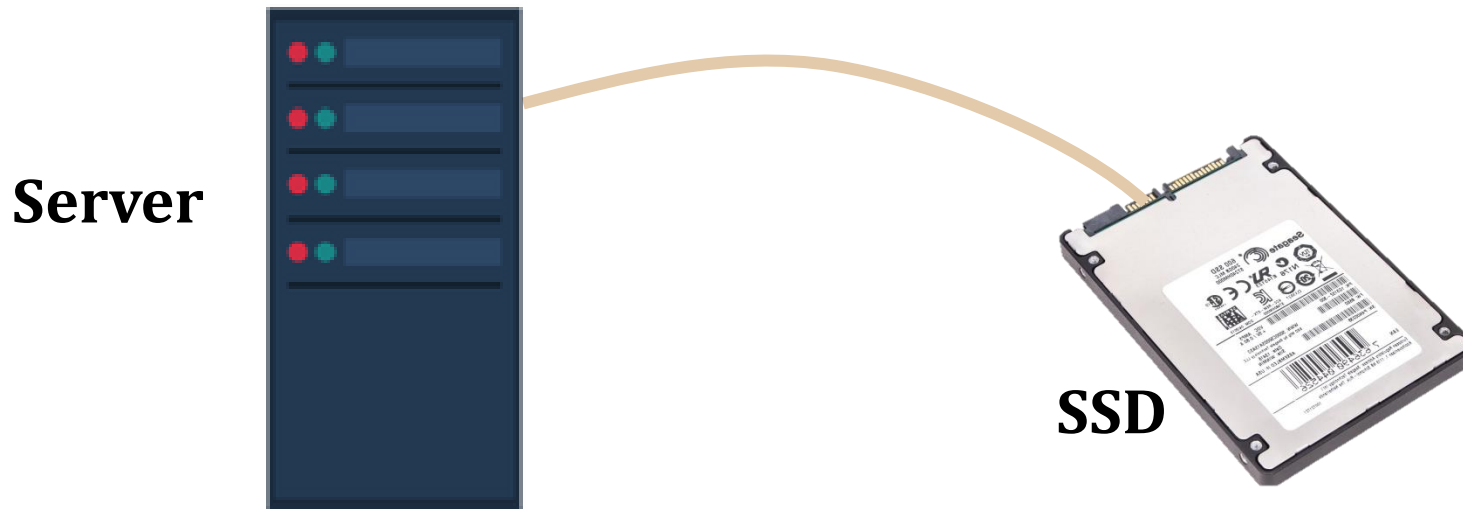
# Process Variation Across Layers



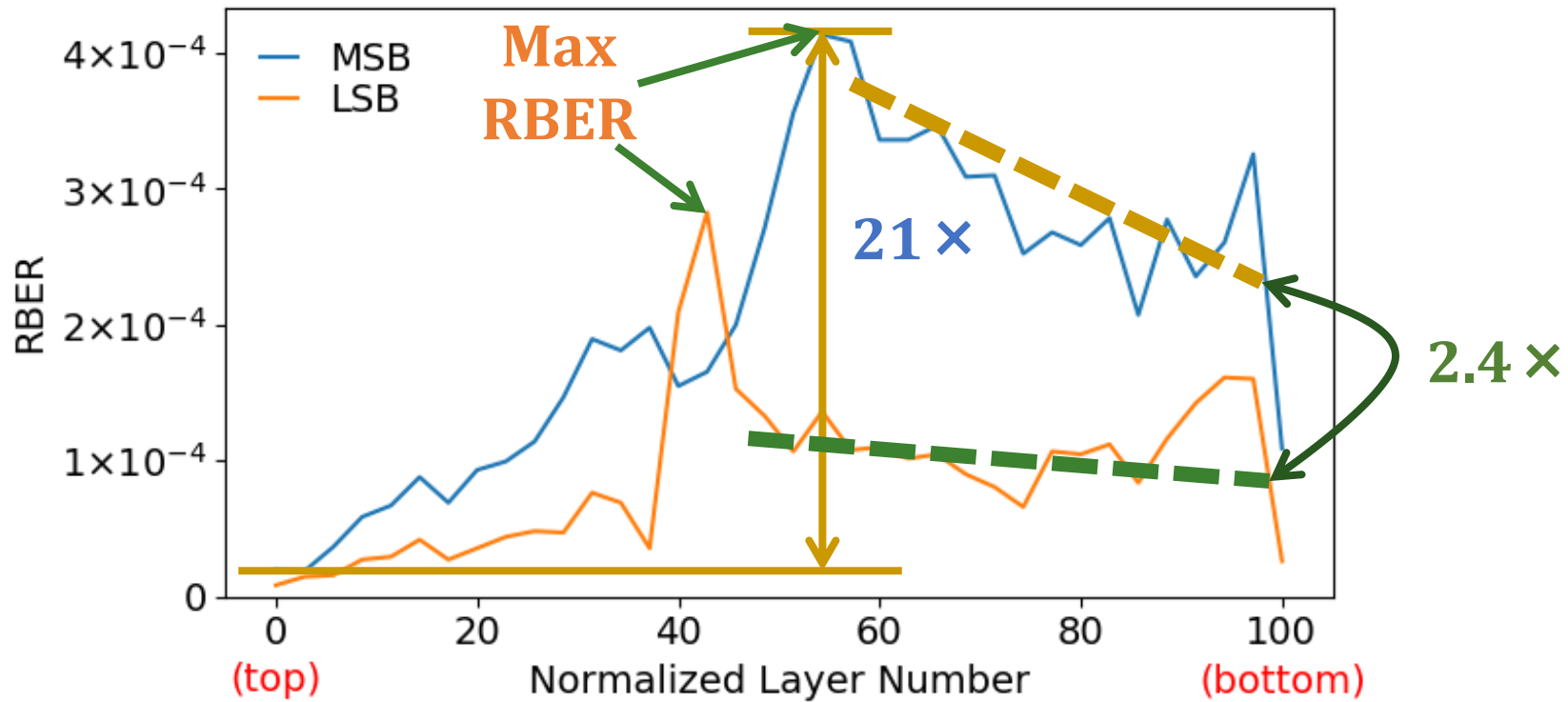
# Characterization Methodology

---

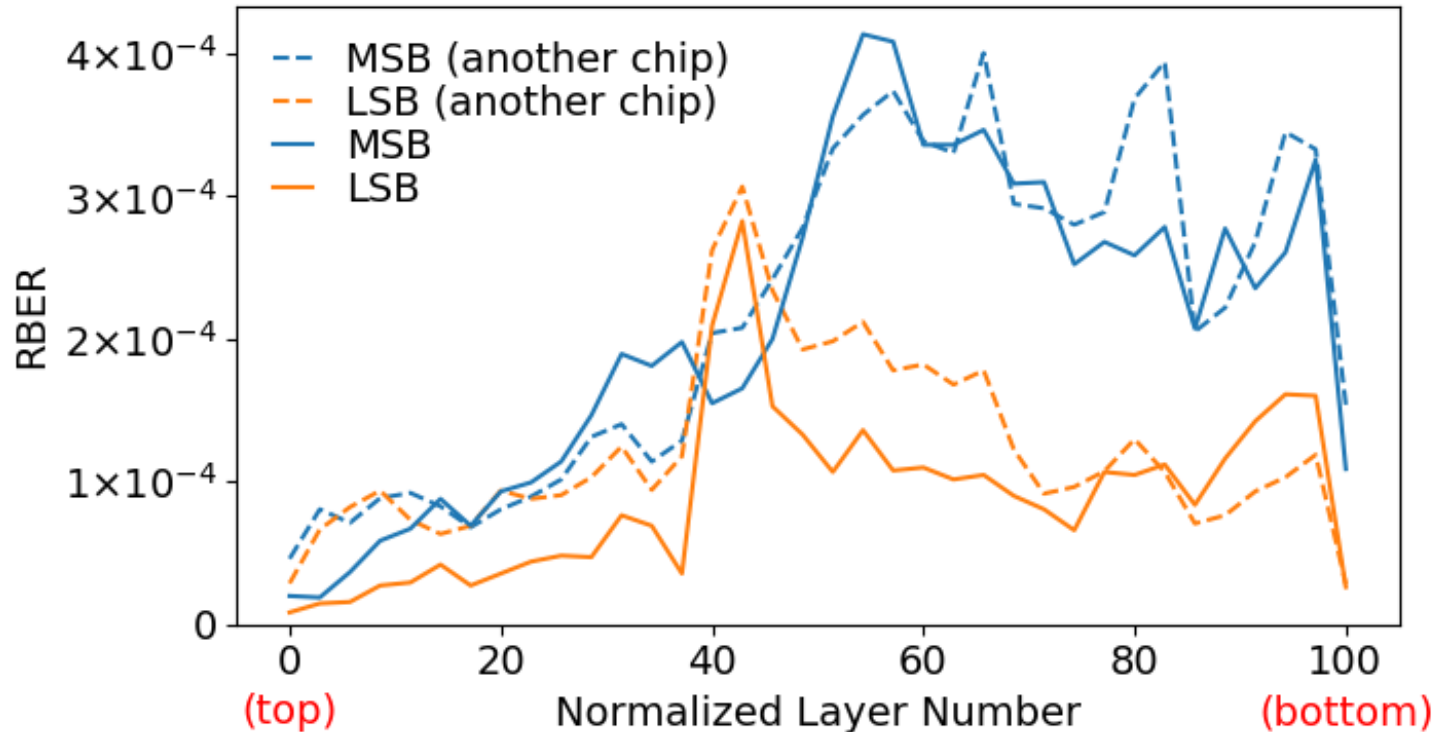
- Modified firmware version in the flash controller
  - ❑ Controls the read reference voltage of the flash chip
  - ❑ Bypasses ECC to get raw data (with raw bit errors)
- Analysis and post-processing of the data on the server



# Layer-to-Layer Process Variation



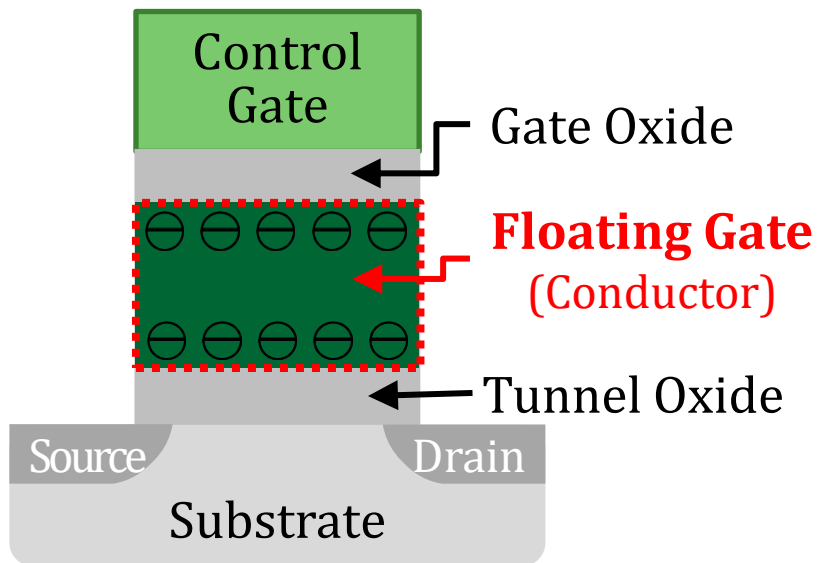
# Layer-to-Layer Process Variation



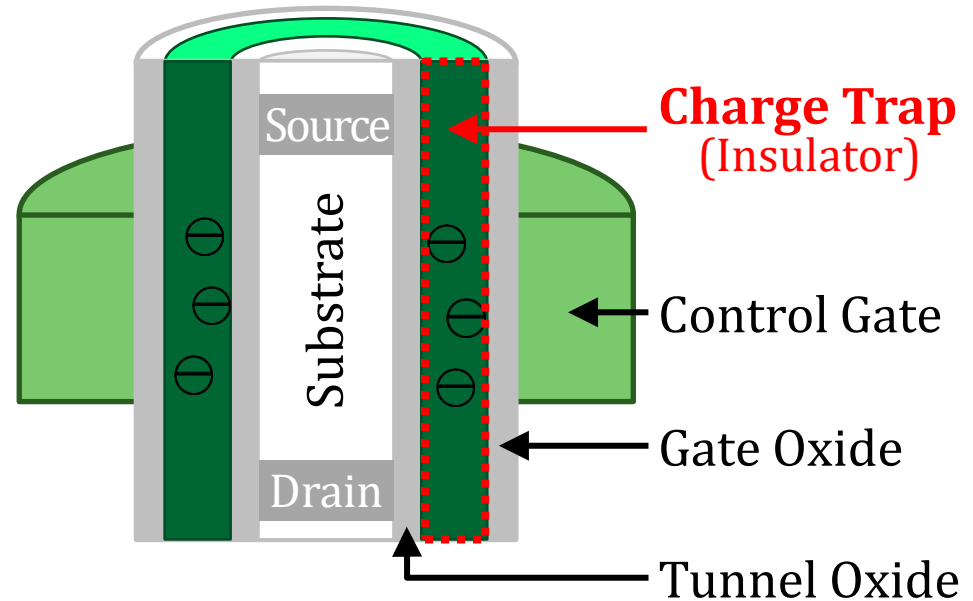
**Large RBER variation  
across layers and LSB-MSB pages**

# Retention Loss Phenomenon

## Planar NAND Cell

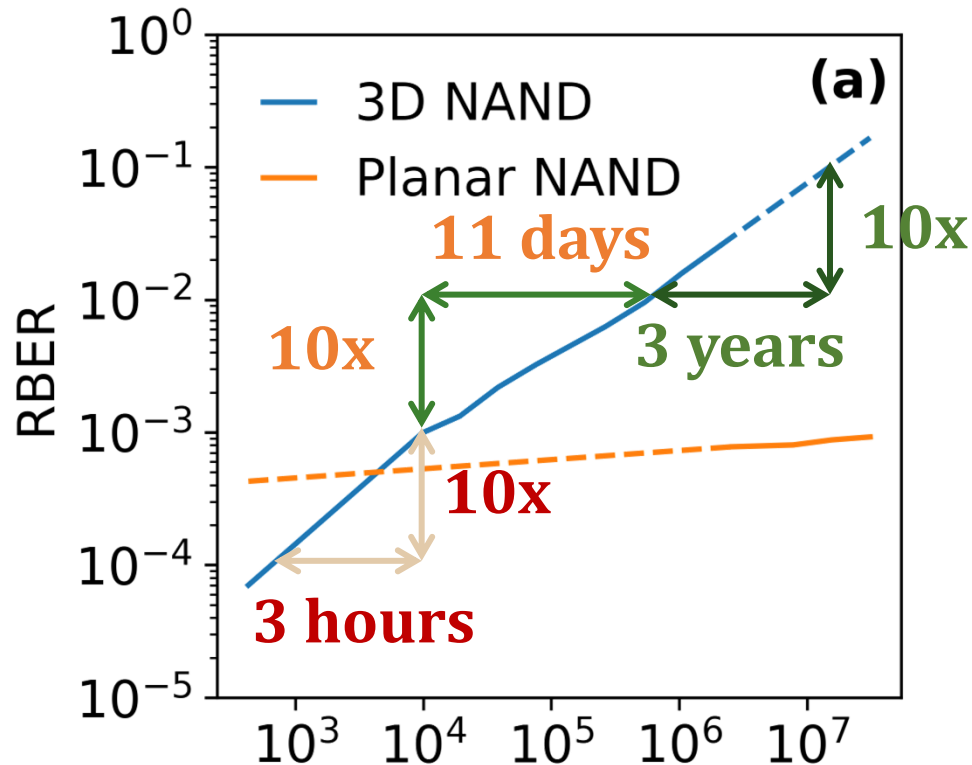


## 3D NAND Cell



**Most dominant type of error in planar NAND.  
Is this true for 3D NAND as well?**

# Early Retention Loss



**Retention errors increase quickly immediately after programming**



# Characterization Summary

---

## ■ Layer-to-layer process variation

- ❑ Large RBER variation across layers and LSB-MSB pages
- ❑ → Need new mechanisms to tolerate RBER variation!

## ■ Early retention loss

- ❑ RBER increases quickly after programming
- ❑ → Need new mechanisms to tolerate retention errors!

## ■ Retention interference

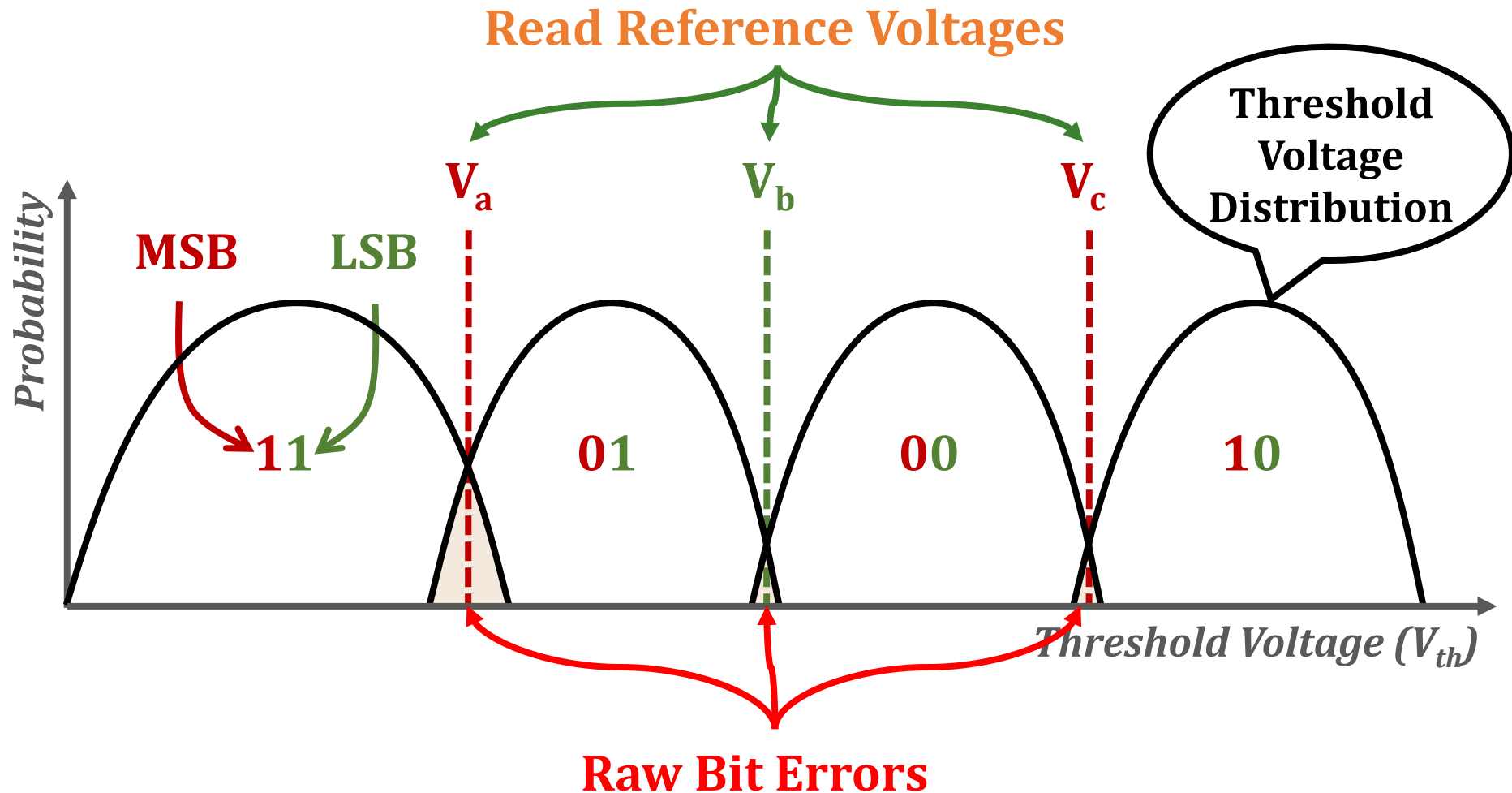
- ❑ Amount of retention loss correlated with neighbor

# Agenda

---

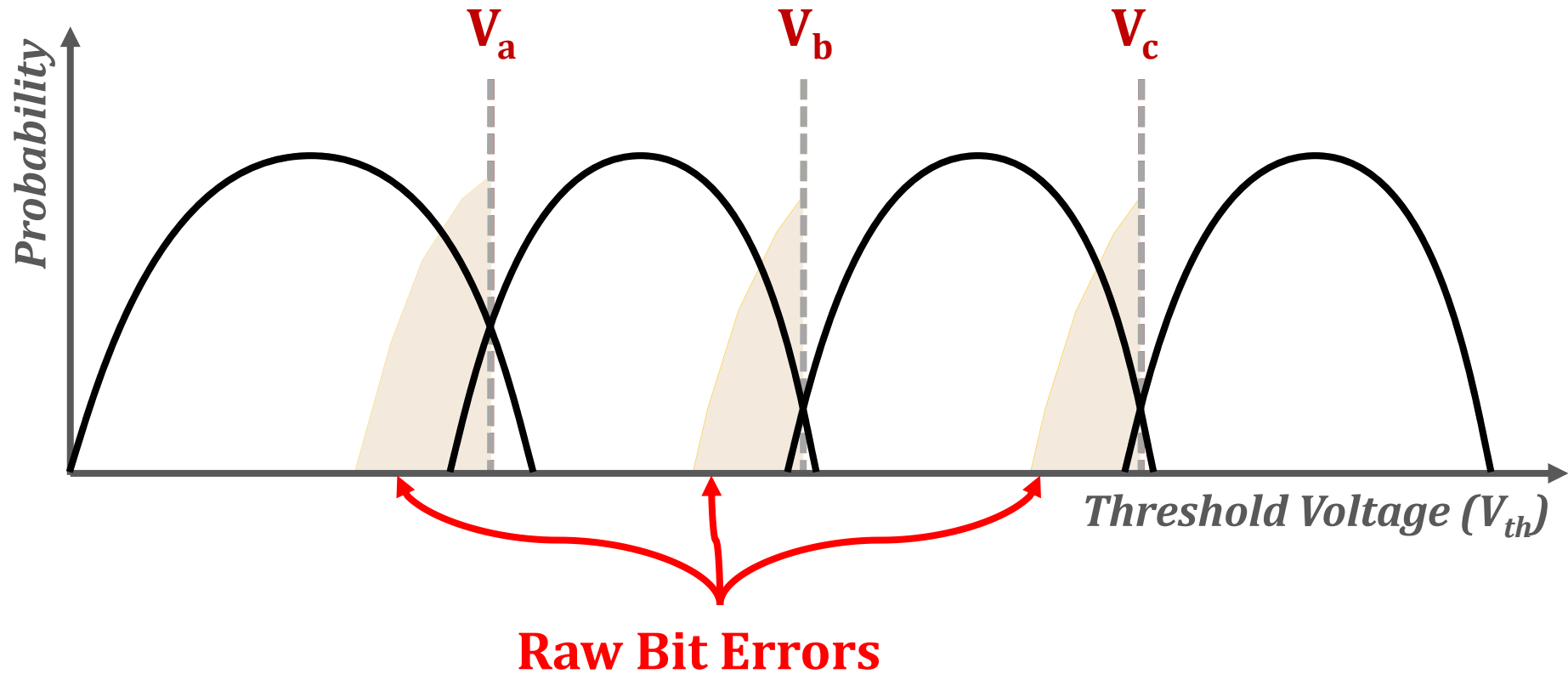
- Background & Introduction
- Contribution 1: Characterize real 3D NAND flash chips
- Contribution 2: Model RBER and threshold voltage
  - Retention loss model
  - RBER variation model

# What Do We Model?

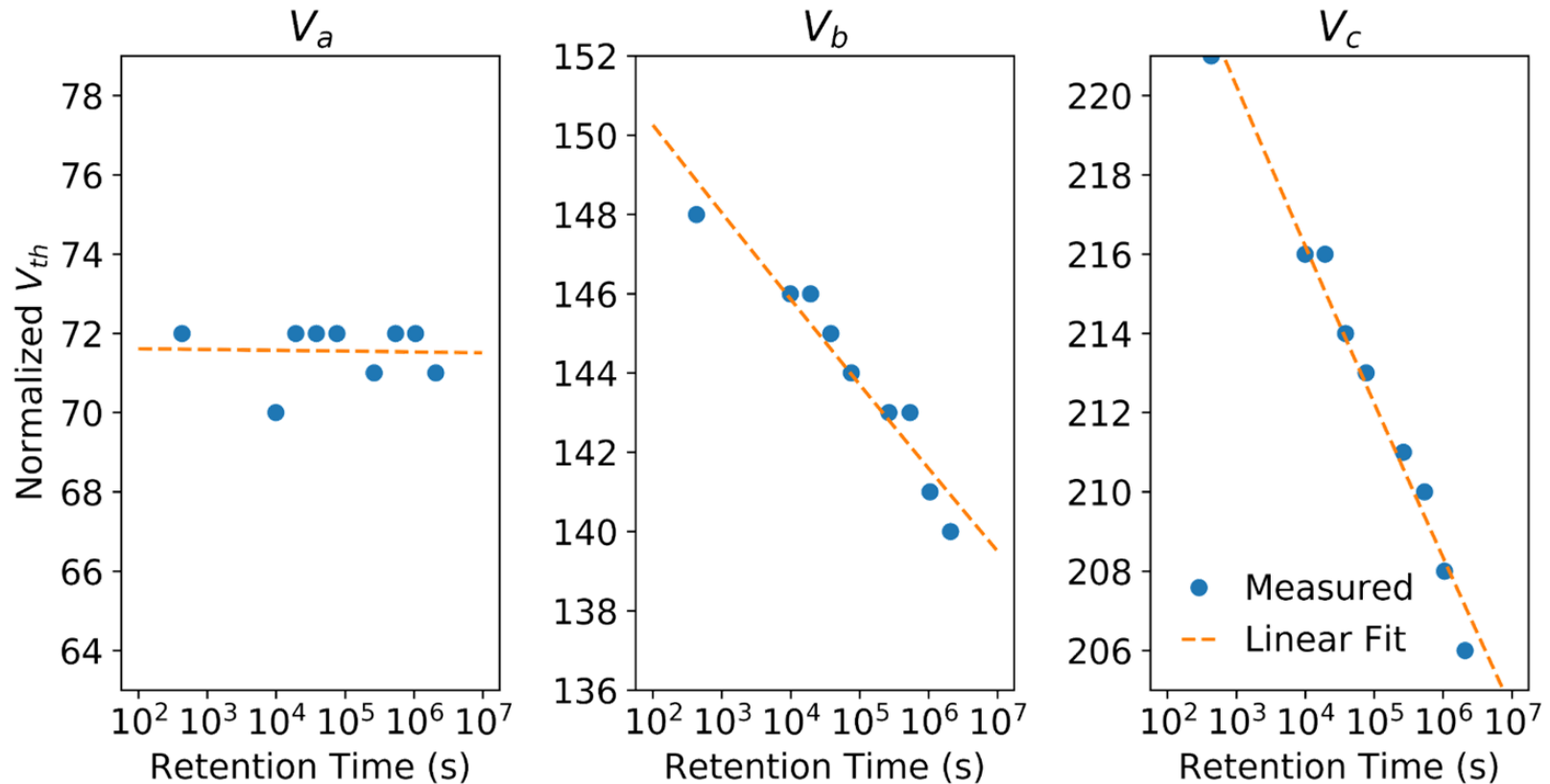


# Optimal Read Reference Voltage

---



# Retention Loss Model



**Early retention loss can be modeled as a simple linear function of  $\log(\text{retention time})$**

# Retention Loss Model

---

- Goal: Develop a simple linear model that can be used online

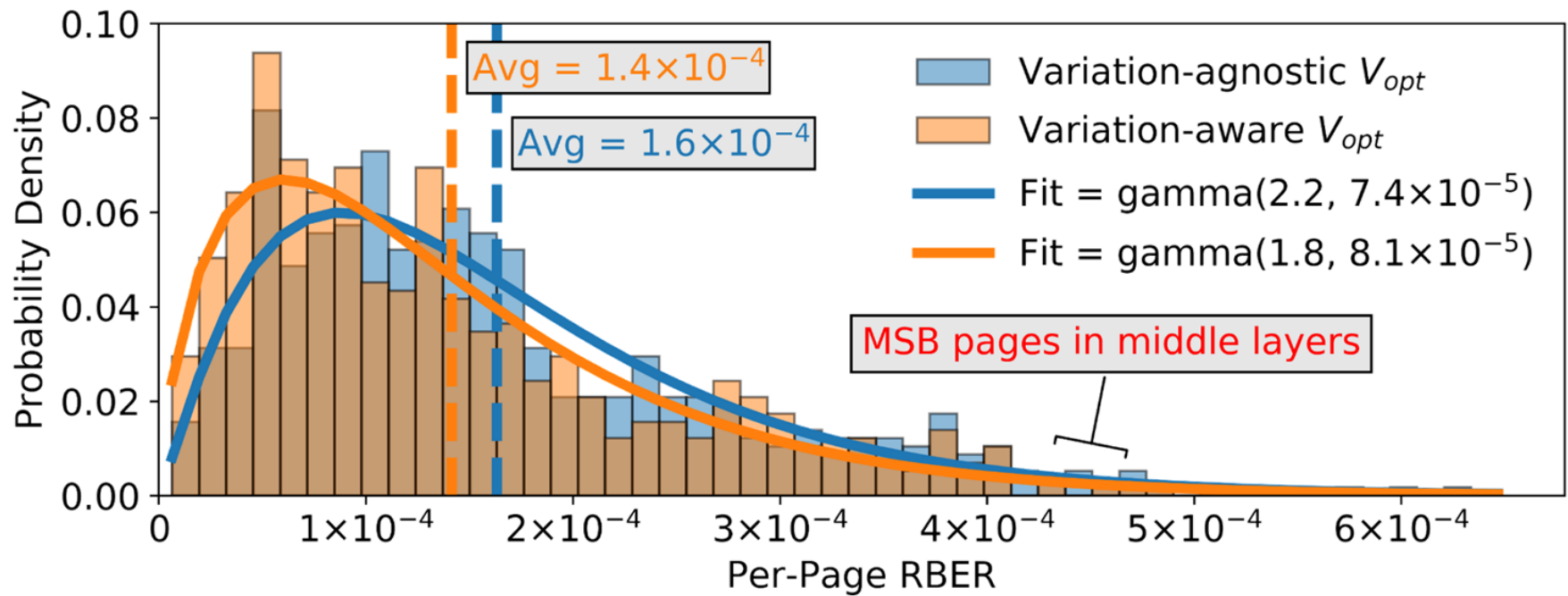
- **Models**

- Optimal read reference voltage ( $V_b$  and  $V_c$ )
- Raw bit error rate ( $\log(RBER)$ )
- Mean and standard deviation of threshold voltage distribution ( $\mu$  and  $\sigma$ )

- **As a function of**

---

# RBER Variation Model



## Variation-agnostic $V_{opt}$

- Same  $V_{ref}$  for all layers optimized for the entire block

**RBER distribution follows gamma distribution**

**KL-divergence error = 0.09**

# Agenda

---

- Background & Introduction
- Contribution 1: Characterize real 3D NAND flash chips
- Contribution 2: Model RBER and threshold voltage
- Contribution 3: Mitigate 3D NAND flash



# LaVAR: Layer Variation Aware Reading

---

- Layer-to-layer process variation
  - Error characteristics are different in each layer
- Goal: Adjust read reference voltage for each layer
- Key Idea: Learn a *voltage offset (Offset)* for each layer
  - $V_{opt}^{Layer\ aware} = V_{opt}^{Layer\ agnostic} + Offset$

# LI-RAID: Layer-Interleaved RAID

---

- Layer-to-layer process variation
  - Worst-case RBER much higher than average RBER
- Goal: Significantly reduce worst-case RBER
- Key Idea
  - Group flash pages on *less reliable layers* with pages on *more reliable layers*
  - Group *MSB pages* with *LSB pages*

# Conventional RAID

<i>Wordline #</i>	<i>Layer #</i>	<i>Page</i>	Chip 0	Chip 1	Chip 2	Chip 3
0	0	<i>MSB</i>	Group 0	Group 0	Group 0	Group 0
0	0	<i>LSB</i>	Group 1	Group 1	Group 1	Group 1
1	1	<i>MSB</i>	Group 2	Group 2	Group 2	Group 2
1	1	<i>LSB</i>	Group 3	Group 3	Group 3	Group 3
2	2	<i>MSB</i>	Group 4	Group 4	Group 4	Group 4
2	2	<i>LSB</i>	Group 5	Group 5	Group 5	Group 5
3	3	<i>MSB</i>	Group 6	Group 6	Group 6	Group 6
3	3	<i>LSB</i>	Group 7	Group 7	Group 7	Group 7

**Worst-case RBER in any layer  
limits the lifetime of conventional RAID**

# LI-RAID: Layer-Interleaved RAID

<i>Wordline #</i>	<i>Layer #</i>	<i>Page</i>	Chip 0	Chip 1	Chip 2	Chip 3
0	0	<i>MSB</i>	Group 0	Blank	Group 4	Group 3
0	0	<i>LSB</i>	Group 1	Blank	Group 5	Group 2
1	1	<i>MSB</i>	Group 2	Group 1	Blank	Group 5
1	1	<i>LSB</i>	Group 3	Group 0	Blank	Group 4
2	2	<i>MSB</i>	Group 4	Group 3	Group 0	Blank
2	2	<i>LSB</i>	Group 5	Group 2	Group 1	Blank
3	3	<i>MSB</i>	Blank	Group 5	Group 2	Group 1
3	3	<i>LSB</i>	Blank	Group 4	Group 3	Group 0

**Any page with worst-case RBER can be corrected by other reliable pages in the RAID group**

# LI-RAID: Layer-Interleaved RAID

---

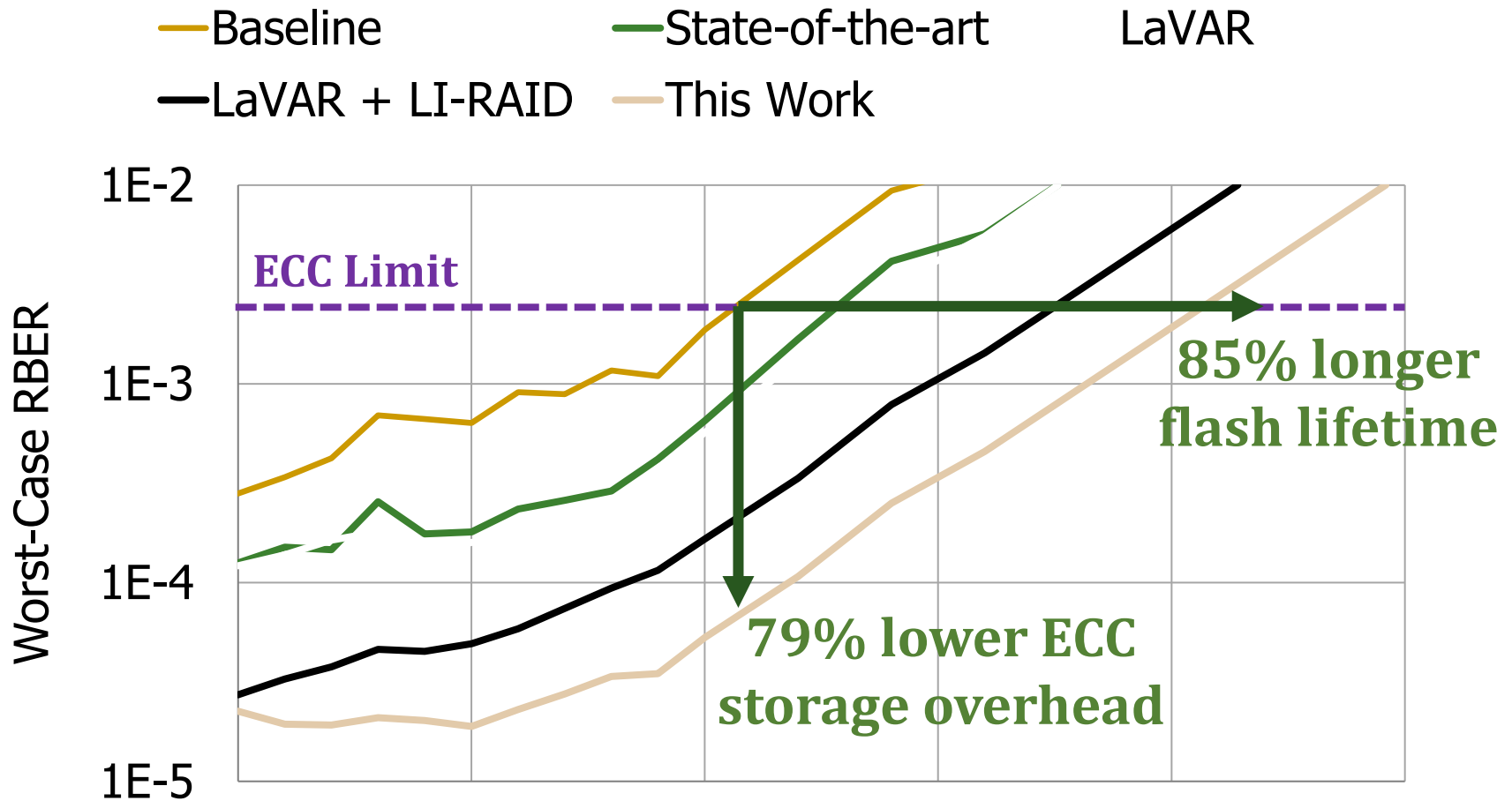
- Layer-to-layer process variation
  - ❑ Worst-case RBER much higher than average RBER
- Goal: Significantly reduce worst-case RBER
- Key Idea
  - ❑ Group flash pages on *less reliable layers* with pages on *more reliable layers*
  - ❑ Group *MSB pages* with *LSB pages*

# ReMAR: Retention Model Aware Reading

---

- Early retention loss
  - Threshold voltage shifts quickly after programming
- Goal: Adjust read reference voltages based on retention loss
- Key Idea: Learn and use a retention loss model online

# Impact on System Reliability



**LaVAR, LI-RAID, and ReMAR improve flash lifetime or reduce ECC overhead significantly**

# Error Mitigation Techniques Summary

---

## ■ LaVAR: Layer Variation Aware Reading

- Learn a  $V_{opt}$  offset for each layer and apply *layer-aware  $V_{opt}$*

## ■ LI-RAID: Layer-Interleaved RAID

- Group flash pages on *less reliable layers* with pages on *more reliable layers*
- Group *MSB pages* with *LSB pages*

## ■ ReMAR: Retention Model Aware Reading

- Learn retention loss model and apply *retention-aware  $V_{opt}$*



# Agenda

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- Background & Introduction
- Contribution 1: Characterize real 3D NAND flash chips
- Contribution 2: Model RBER and threshold voltage
- Contribution 3: Mitigate 3D NAND flash

# Conclusion

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- Problem: 3D NAND error characteristics are not well studied
- Goal: *Understand & mitigate* 3D NAND errors to improve lifetime
- Contribution 1: Characterize real 3D NAND flash chips
  - *Process variation: 21 × error rate difference across layers*
  - *Early retention loss: Error rate increases by 10 × after 3 hours*

# Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation

**Yixin Luo**

**Saugata Ghose**

**Yu Cai**

**Erich F. Haratsch**

**Onur Mutlu**

**Carnegie Mellon**



**ETH** Zürich

**SAFARI**



# 3D NAND Flash Reliability II [SIGMETRICS'18]

---

- Yixin Luo, Saugata Ghose, Yu Cai, Erich F. Haratsch, and Onur Mutlu,  
**"Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (**SIGMETRICS**), Irvine, CA, USA, June 2018.*  
[[Abstract](#)]

## Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation

Yixin Luo<sup>†</sup>

Saugata Ghose<sup>†</sup>

Yu Cai<sup>†</sup>

Erich F. Haratsch<sup>‡</sup>

Onur Mutlu<sup>§†</sup>

<sup>†</sup>Carnegie Mellon University

<sup>‡</sup>Seagate Technology

<sup>§</sup>ETH Zürich

# One More Idea

# WARM

Write-hotness Aware Retention Management

**Yixin Luo**, Yu Cai, Saugata Ghose, Jongmoo Choi\*,  
Onur Mutlu

Carnegie Mellon University, \*Dankook University

**SAFARI**

**Carnegie Mellon**

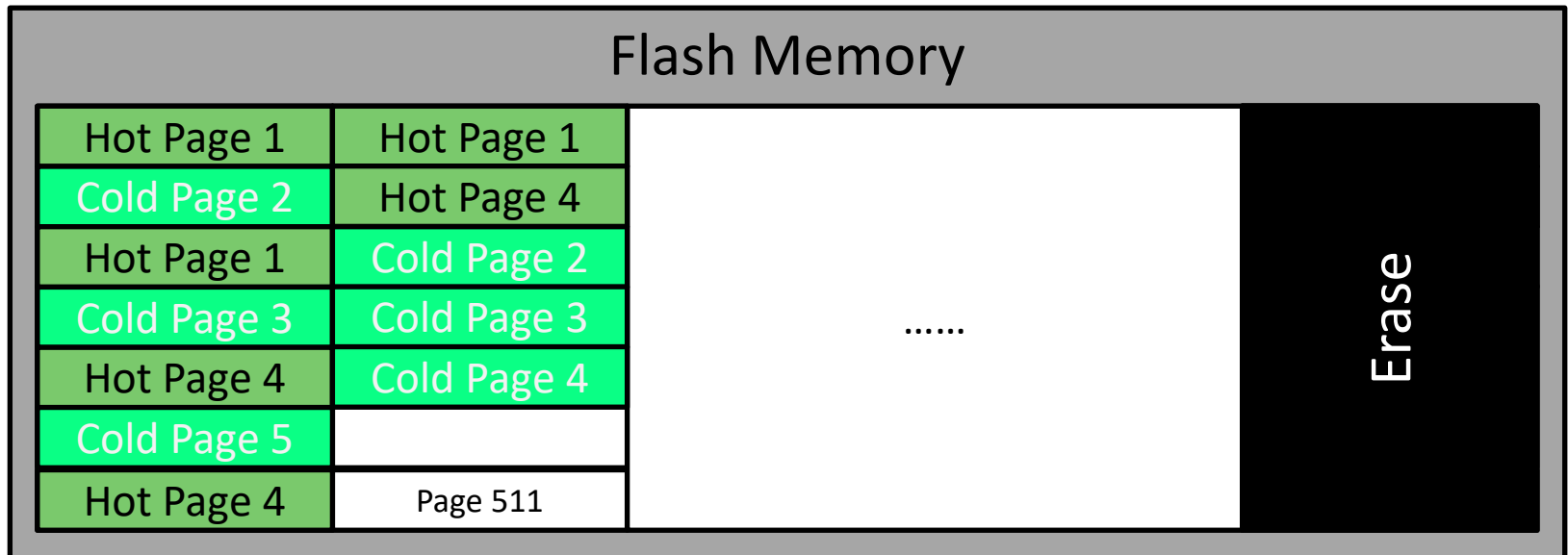


# Executive Summary

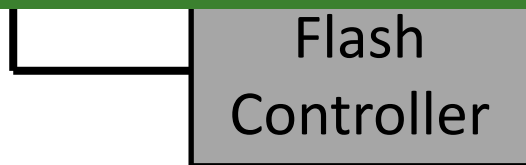
---

- Flash memory can achieve **50x endurance improvement by relaxing retention time using refresh** [Cai+ ICCD '12]
- Problem: **Frequent refresh consumes the majority of endurance improvement**
- Goal: Reduce refresh overhead to increase flash memory lifetime
- Key Observation: **Refresh is unnecessary for write-hot data**
- Key Ideas of Write-hotness Aware Retention Management (WARM)
  - **Physically partition write-hot pages and write-cold pages** within the flash drive
  - **Apply different policies** (garbage collection, wear-leveling, refresh) to each group
- Key Results
  - WARM w/o refresh **improves lifetime by 3.24x**
  - WARM w/ adaptive refresh **improves lifetime by 12.9x** (1.21x over refresh only)

# Conventional Write-Hotness Oblivious Management

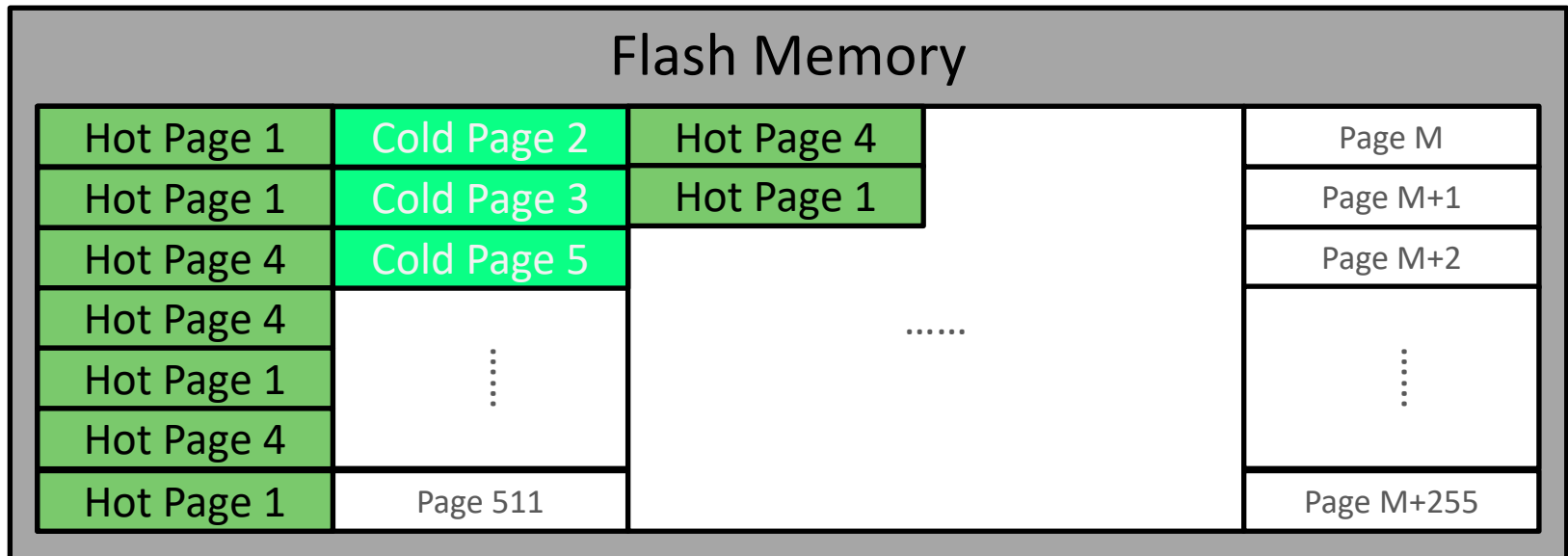


Unable to relax retention time for blocks with write-hot and cold pages

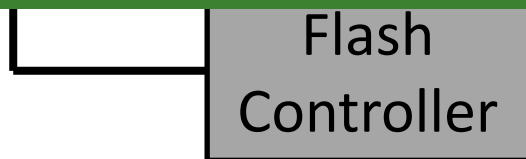




# Key Idea: Write-Hotness Aware Management



Can relax retention time for blocks with write-hot pages only



# Write-Hotness Aware Retention Management

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- Yixin Luo, Yu Cai, Saugata Ghose, Jongmoo Choi, and Onur Mutlu,  
**"WARM: Improving NAND Flash Memory Lifetime with Write-hotness Aware Retention Management"**  
*Proceedings of the 31st International Conference on Massive Storage Systems and Technologies (MSST)*, Santa Clara, CA, June 2015.  
[[Slides \(pptx\)](#)] [[pdf](#)] [[Poster \(pdf\)](#)]

## WARM: Improving NAND Flash Memory Lifetime with Write-hotness Aware Retention Management

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Jongmoo Choi<sup>†</sup>  
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Onur Mutlu  
onur@cmu.edu

# Agenda

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- Background, Motivation and Approach
- Experimental Characterization Methodology
- Error Analysis and Management
  - Main Characterization Results
  - Retention-Aware Error Management
  - Threshold Voltage and Program Interference Analysis
  - Read Reference Voltage Prediction
  - Neighbor-Assisted Error Correction
  - Read Disturb Error Handling
  - Retention Error Handling
  - Large Scale Field Analysis
  - 3D NAND Flash Memory Reliability
- Summary

# Summary of Key Works

---

- Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu,  
**"Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives"**

*Proceedings of the IEEE*, September 2017.

Cai+, "Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis," DATE 2012.

Cai+, "Flash Correct-and-Refresh: Retention-Aware Error Management for Increased Flash Memory Lifetime," ICCD 2012.

Cai+, "Threshold Voltage Distribution in MLC NAND Flash Memory: Characterization, Analysis and Modeling," DATE 2013.

Cai+, "Error Analysis and Retention-Aware Error Management for NAND Flash Memory," Intel Technology Journal 2013.

Cai+, "Program Interference in MLC NAND Flash Memory: Characterization, Modeling, and Mitigation," ICCD 2013.

Cai+, "Neighbor-Cell Assisted Error Correction for MLC NAND Flash Memories," SIGMETRICS 2014.

Cai+, "Data Retention in MLC NAND Flash Memory: Characterization, Optimization and Recovery," HPCA 2015.

Cai+, "Read Disturb Errors in MLC NAND Flash Memory: Characterization and Mitigation," DSN 2015.

Luo+, "WARM: Improving NAND Flash Memory Lifetime with Write-hotness Aware Retention Management," MSST 2015.

Meza+, "A Large-Scale Study of Flash Memory Errors in the Field," SIGMETRICS 2015.

Luo+, "Enabling Accurate and Practical Online Flash Channel Modeling for Modern MLC NAND Flash Memory," IEEE JSAC 2016.

Cai+, "Vulnerabilities in MLC NAND Flash Memory Programming: Experimental Analysis, Exploits, and Mitigation Techniques," HPCA 2017.

Fukami+, "Improving the Reliability of Chip-Off Forensic Analysis of NAND Flash Memory Devices," DFRWS EU 2017.

Luo+, "HeatWatch: Improving 3D NAND Flash Memory Device Reliability by Exploiting Self-Recovery and Temperature-Awareness," HPCA 2018.

Luo+, "Improving 3D NAND Flash Memory Lifetime by Tolerating Early Retention Loss and Process Variation," SIGMETRICS 2018.

---

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.

# NAND Flash Vulnerabilities [HPCA'17]

*HPCA, Feb. 2017*

## Vulnerabilities in MLC NAND Flash Memory Programming: Experimental Analysis, Exploits, and Mitigation Techniques

Yu Cai<sup>†</sup>   Saugata Ghose<sup>†</sup>   Yixin Luo<sup>‡†</sup>   Ken Mai<sup>†</sup>   Onur Mutlu<sup>§†</sup>   Erich F. Haratsch<sup>‡</sup>  
<sup>†</sup>Carnegie Mellon University   <sup>‡</sup>Seagate Technology   <sup>§</sup>ETH Zürich

*Modern NAND flash memory chips provide high density by storing two bits of data in each flash cell, called a multi-level cell (MLC). An MLC partitions the threshold voltage range of a flash cell into four voltage states. When a flash cell is programmed, a high voltage is applied to the cell. Due to parasitic capacitance coupling between flash cells that are physically close to each other, flash cell programming can lead to cell-to-cell program interference, which introduces errors into neighboring flash cells. In order to reduce the impact of cell-to-cell interference on the reliability of MLC NAND flash memory, flash manufacturers adopt a two-step programming method, which programs the MLC in two separate steps. First, the flash memory partially programs the least significant bit of the MLC to some intermediate threshold voltage. Second, it programs the most significant bit to bring the MLC up to its full voltage state.*

*In this paper, we demonstrate that two-step programming exposes new reliability and security vulnerabilities. We expe-*

*belongs to a different flash memory page (the unit of data programmed and read at the same time), which we refer to, respectively, as the least significant bit (LSB) page and the most significant bit (MSB) page [5].*

*A flash cell is programmed by applying a large voltage on the control gate of the transistor, which triggers charge transfer into the floating gate, thereby increasing the threshold voltage. To precisely control the threshold voltage of the cell, the flash memory uses incremental step pulse programming (ISPP) [12, 21, 25, 41]. ISPP applies multiple short pulses of the programming voltage to the control gate, in order to increase the cell threshold voltage by some small voltage amount ( $V_{step}$ ) after each step. Initial MLC designs programmed the threshold voltage in one shot, issuing all of the pulses back-to-back to program both bits of data at the same time. However, as flash memory scales down, the distance between neighboring flash cells decreases, which*

[https://people.inf.ethz.ch/omutlu/pub/flash-memory-programming-vulnerabilities\\_hpca17.pdf](https://people.inf.ethz.ch/omutlu/pub/flash-memory-programming-vulnerabilities_hpca17.pdf)



*Proceedings of the IEEE, Sept. 2017*



## Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

*This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.*

By YU CAI, SAUGATA GHOSE, ERICH F. HARATSCH, YIXIN LUO, AND ONUR MUTLU

<https://arxiv.org/pdf/1706.08642>

# More Up-to-date Version

---

- Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu, **"Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery"**  
*Invited Book Chapter in Inside Solid State Drives, 2018.*  
[Preliminary arxiv.org version]

## Errors in Flash-Memory-Based Solid-State Drives: Analysis, Mitigation, and Recovery

YU CAI, SAUGATA GHOSE

Carnegie Mellon University

ERICH F. HARATSCH

Seagate Technology

YIXIN LUO

Carnegie Mellon University

ONUR MUTLU

ETH Zürich and Carnegie Mellon University

# P&S Modern SSDs

## Flash Memory and Solid-State Drives

Prof. Onur Mutlu

ETH Zürich

Fall 2022

25 January 2023



# Other Works on Flash Memory

# *HeatWatch*

Improving 3D NAND Flash Memory Device Reliability by  
Exploiting Self-Recovery and Temperature Awareness

**Yixin Luo**

**Saugata Ghose**

**Yu Cai**

**Erich F. Haratsch**

**Onur Mutlu**

**Carnegie Mellon**

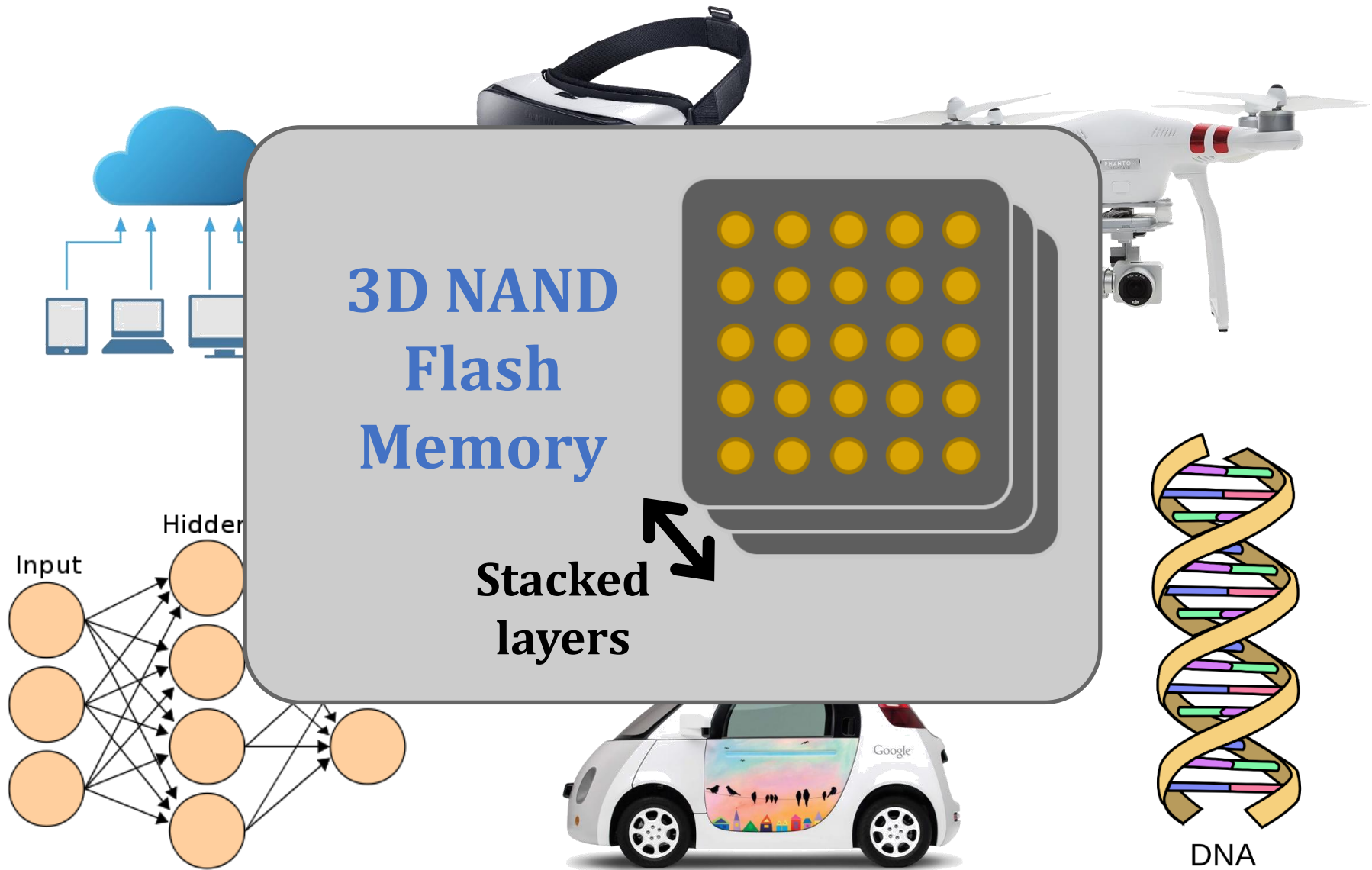


**ETH** zürich

**SAFARI**



# Storage Technology Drivers - 2018



# Executive Summary

---

- 3D NAND flash memory susceptible to **retention errors**
  - ❑ Charge leaks out of flash cell
  - ❑ Two unreported factors: **self-recovery** and

- **Experimental characterization** of *real* 3D NAND chips

- **Unified Self-Recovery and Temperature (URT) Model**

- Predicts impact of retention loss, wearout, self-recovery, temperature on **flash cell voltage**
- **Low prediction error rate: 4.9%**

- **HeatWatch**

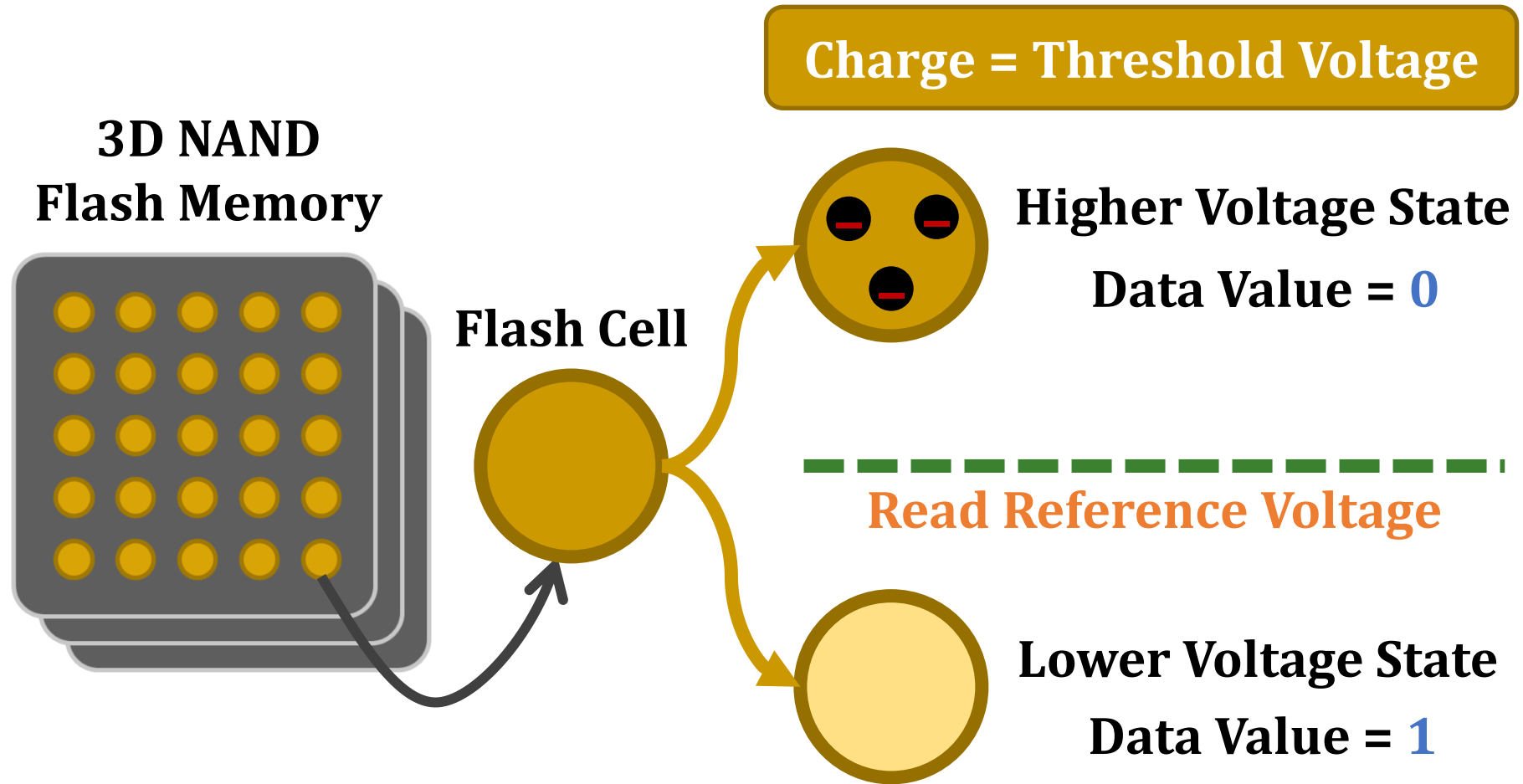
- Uses URT model to find optimal read voltages for 3D NAND flash
- **Improves flash lifetime by 3.85x**

# Outline

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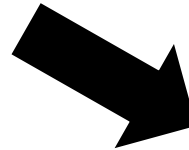
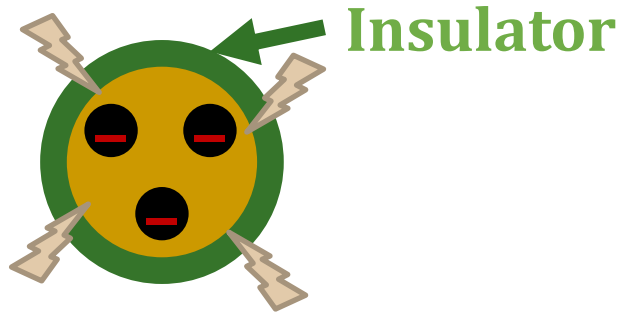
- Executive Summary
- **Background on NAND Flash Reliability**
- Characterization of Self-Recovery and Temperature Effect on Real 3D NAND Flash Memory Chips
- URT: Unified Self-Recovery and Temperature Model
- HeatWatch Mechanism
- Conclusion

# 3D NAND Flash Memory Background



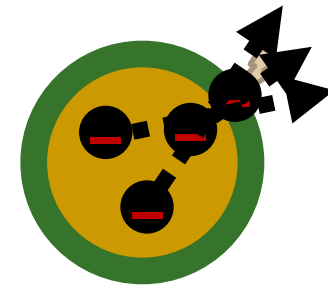
# Flash Wearout

Program/Erase (P/E) → **Wearout**

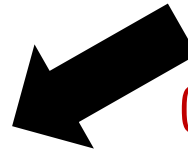


**Wearout Effects:**

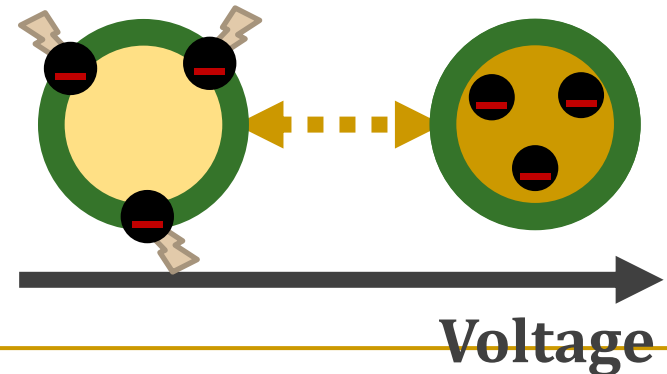
**1. Retention Loss**  
(voltage shift over time)



**2. Program Variation**  
(init. voltage difference b/w states)



**Wearout Introduces Errors**

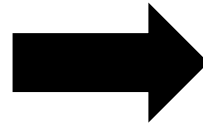


# Improving Flash Lifetime

---

**Errors introduced by wearout**  
**limit flash lifetime**  
(measured in P/E cycles)

**Two Ways to Improve  
Flash Lifetime**



**Exploiting the  
Self-Recovery Effect**

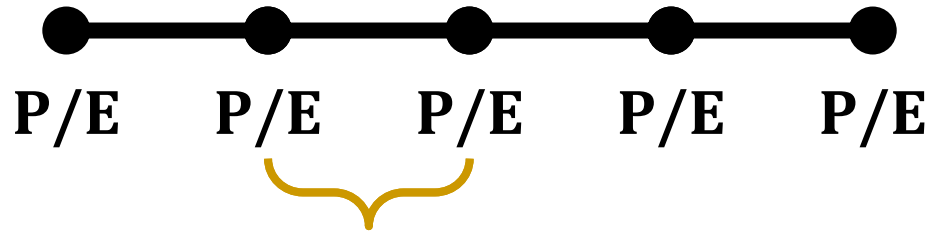
**Exploiting the  
Temperature Effect**



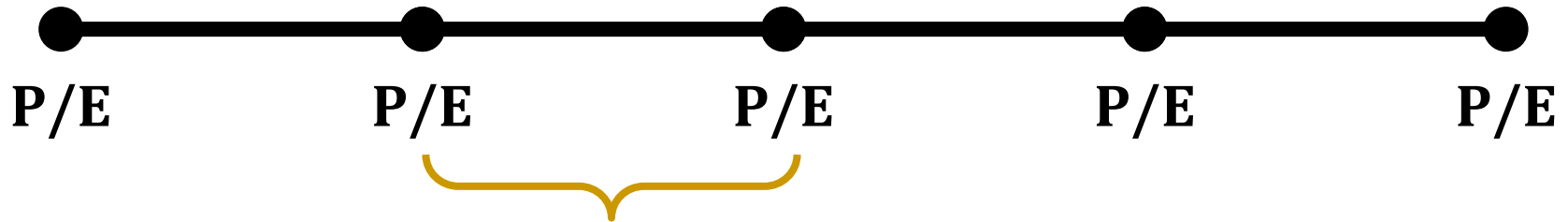
# Exploiting the Self-Recovery Effect

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Partially repairs damage due to wearout



Dwell Time: Idle Time Between P/E Cycles



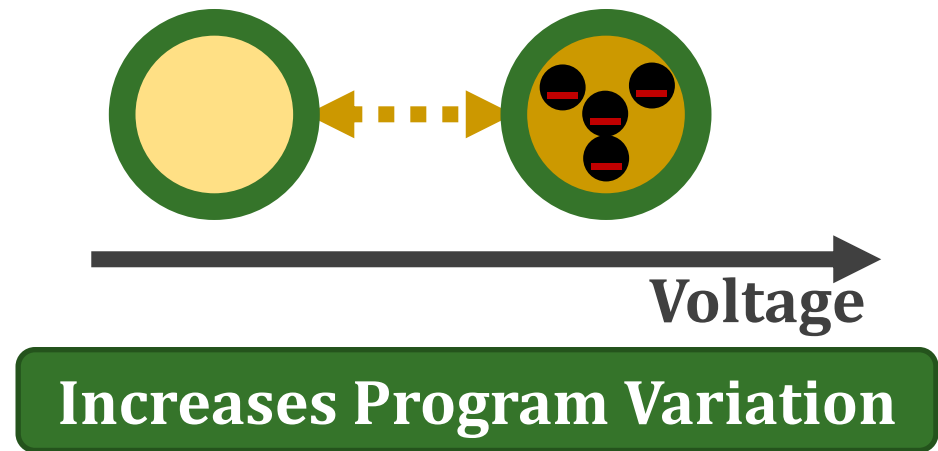
Longer Dwell Time: More Self-Recovery

**Reduces Retention Loss**

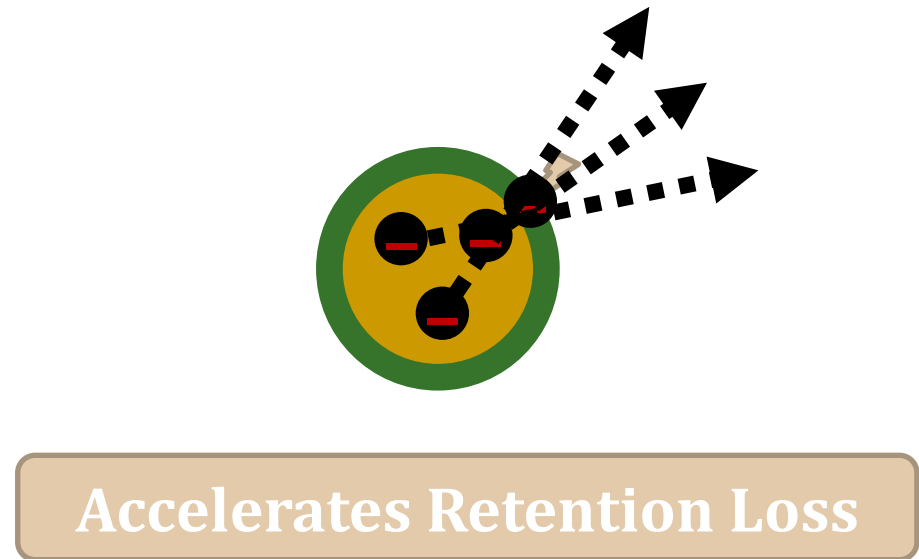
# Exploiting the Temperature Effect

---

**High Program  
Temperature**



**High Storage  
Temperature**



# Prior Studies of Self-Recovery/Temperature

---

## Planar (2D) NAND

## 3D NAND

**Self-Recovery  
Effect**



Mielke 2006



**Temperature  
Effect**



JEDEC 2010  
(no characterization)



# Outline

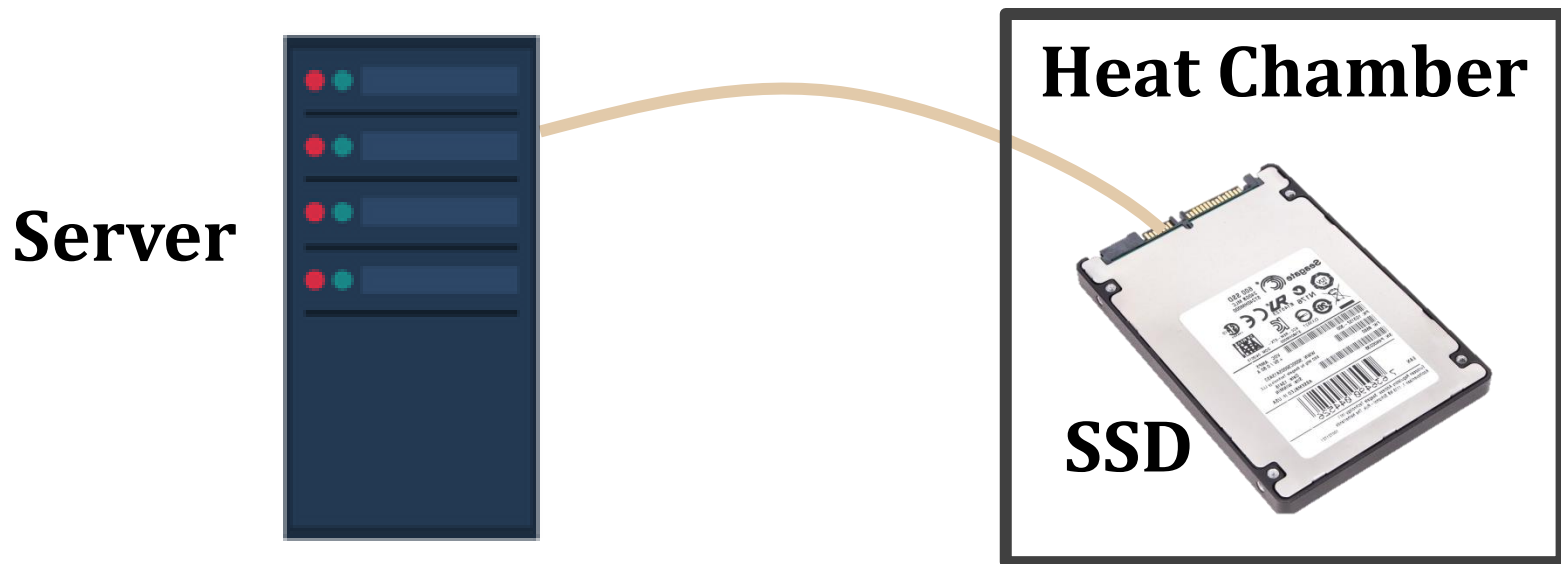
---

- Executive Summary
- Background on NAND Flash Reliability
- **Characterization of Self-Recovery and Temperature Effect on Real 3D NAND Flash Memory Chips**
- URT: Unified Self-Recovery and Temperature Model
- HeatWatch Mechanism
- Conclusion

# Characterization Methodology

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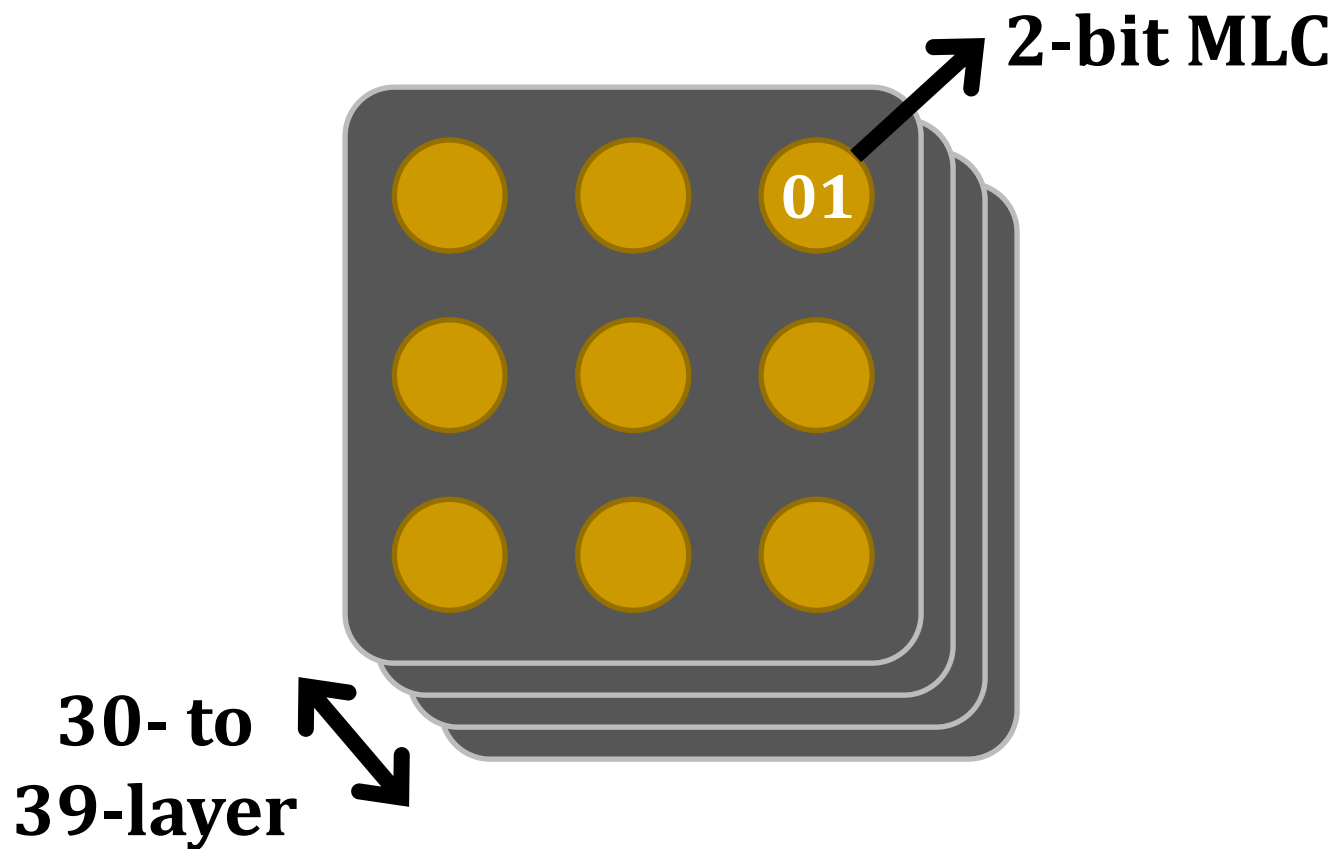
- Modified firmware version in the flash controller
  - ❑ Control the read reference voltage of the flash chip
  - ❑ Bypass ECC to get raw NAND data (with raw bit errors)
- Control temperature with a heat chamber



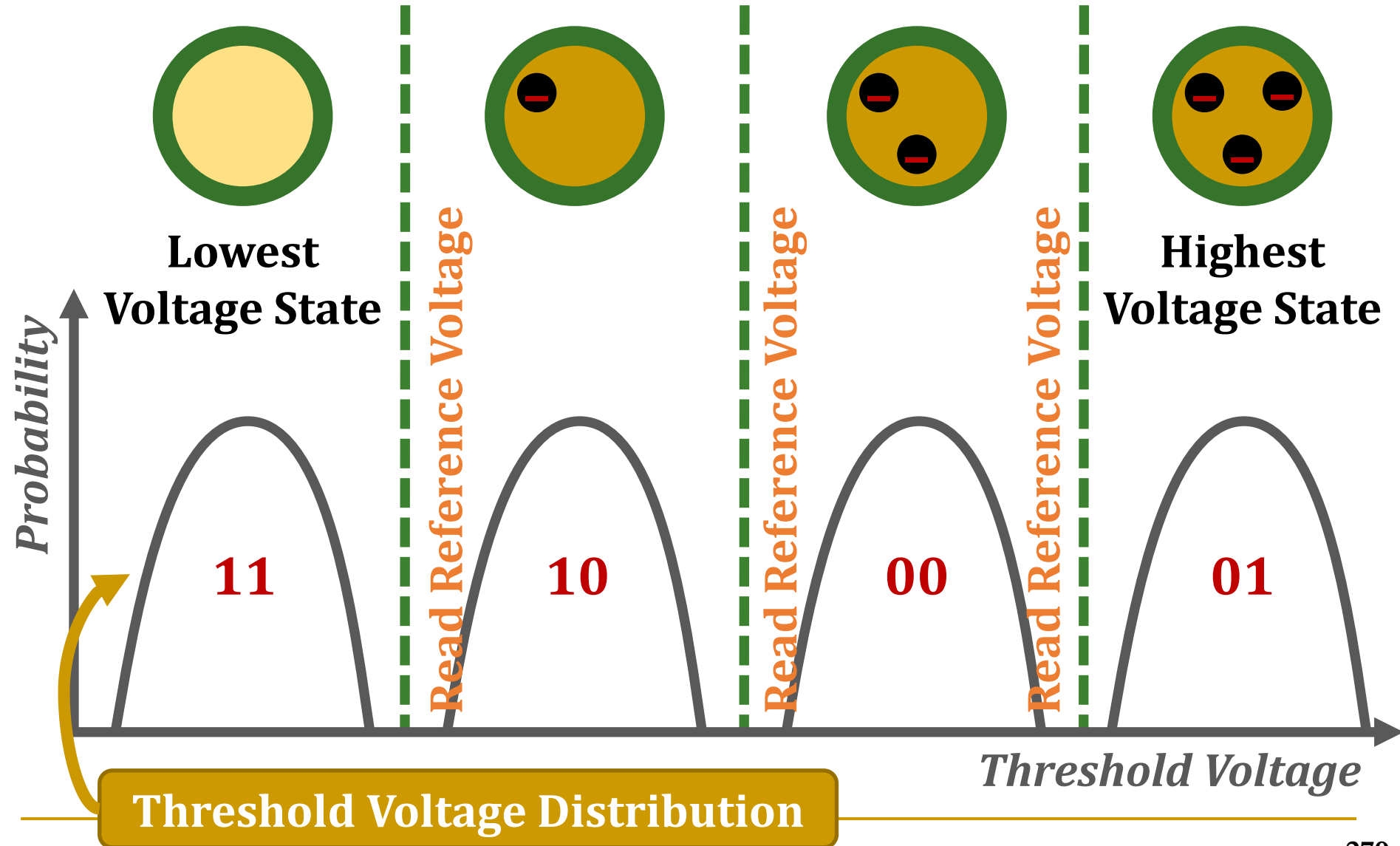
# Characterized Devices

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## Real 30-39 Layer 3D MLC NAND Flash Chips



# MLC Threshold Voltage Distribution Background



# Characterization Goal

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## Characterized Metrics

### Retention Loss Speed

(how fast voltage shifts over time)

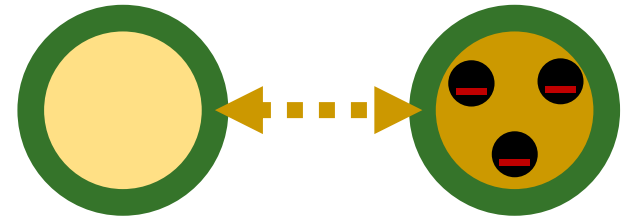
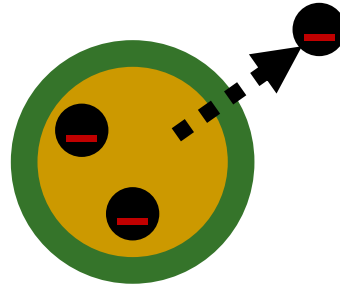
### Program Variation

(initial voltage difference between states)

## Characterized Phenomena

**Self-Recovery Effect**

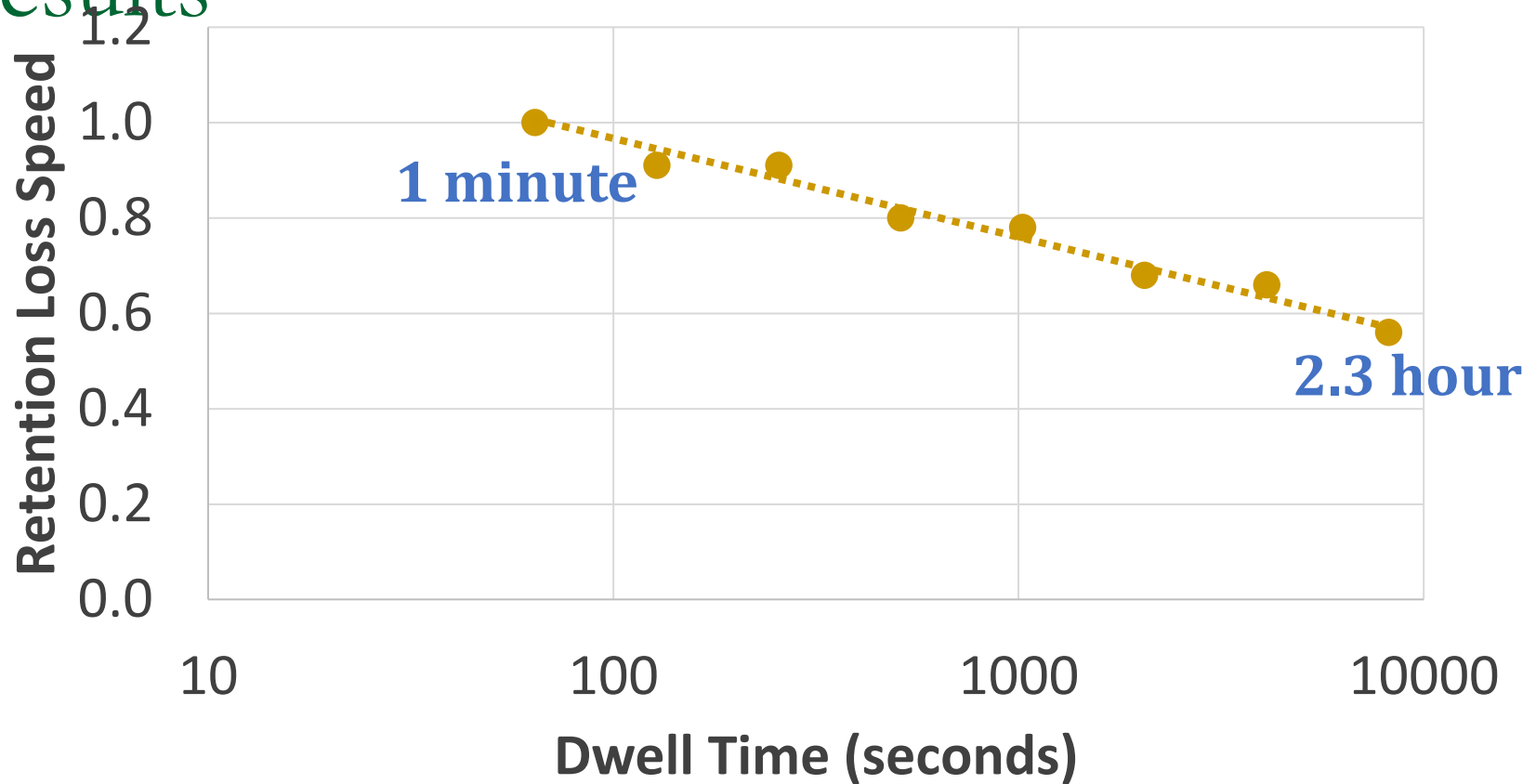
**Temperature Effect**





# Self-Recovery Effect Characterization

## Results

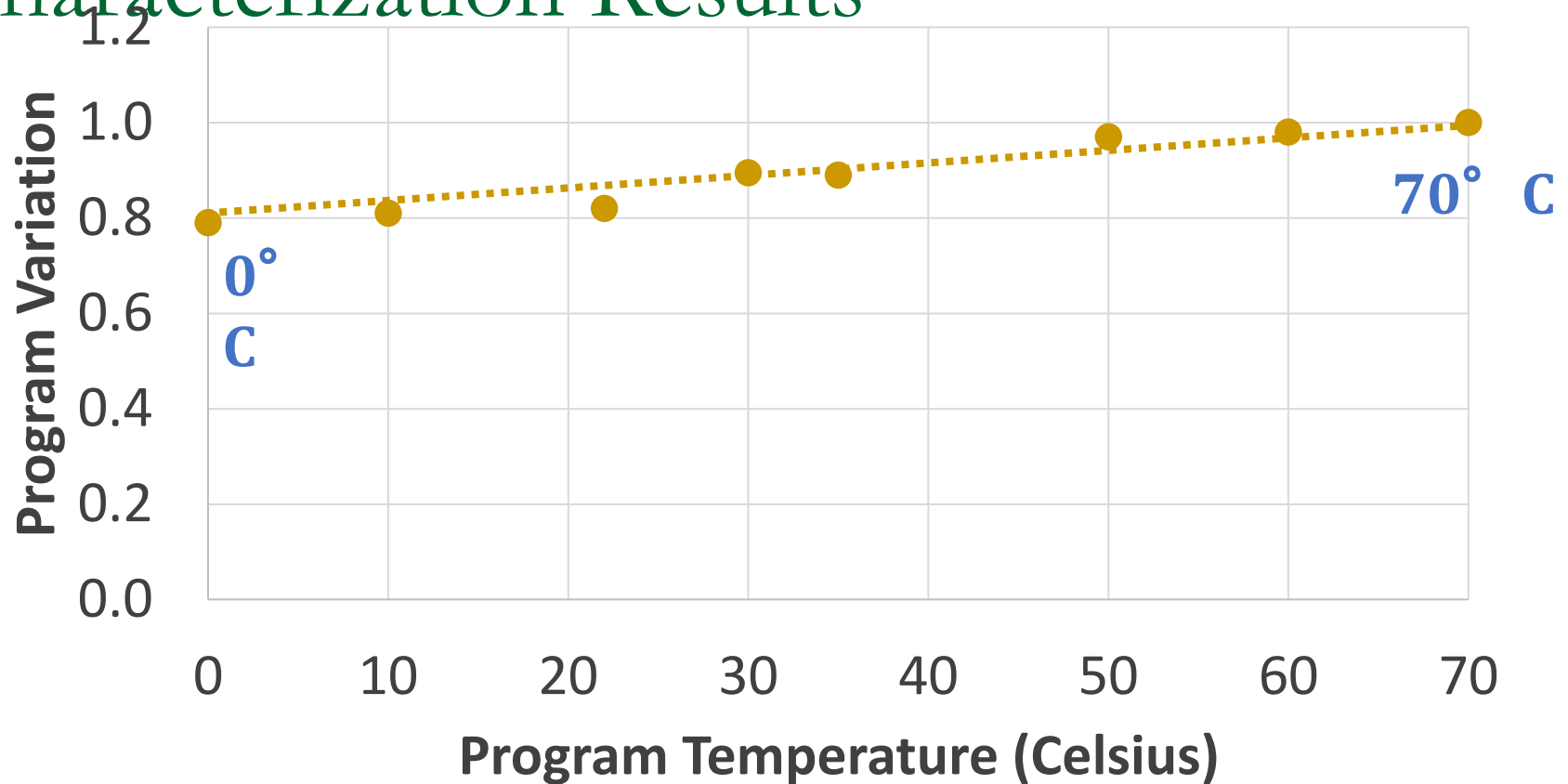


Dwell time: Idle time between P/E cycles

**Increasing dwell time from 1 minute to 2.3 hours slows down retention loss speed by 40%**

# Program Temperature Effect

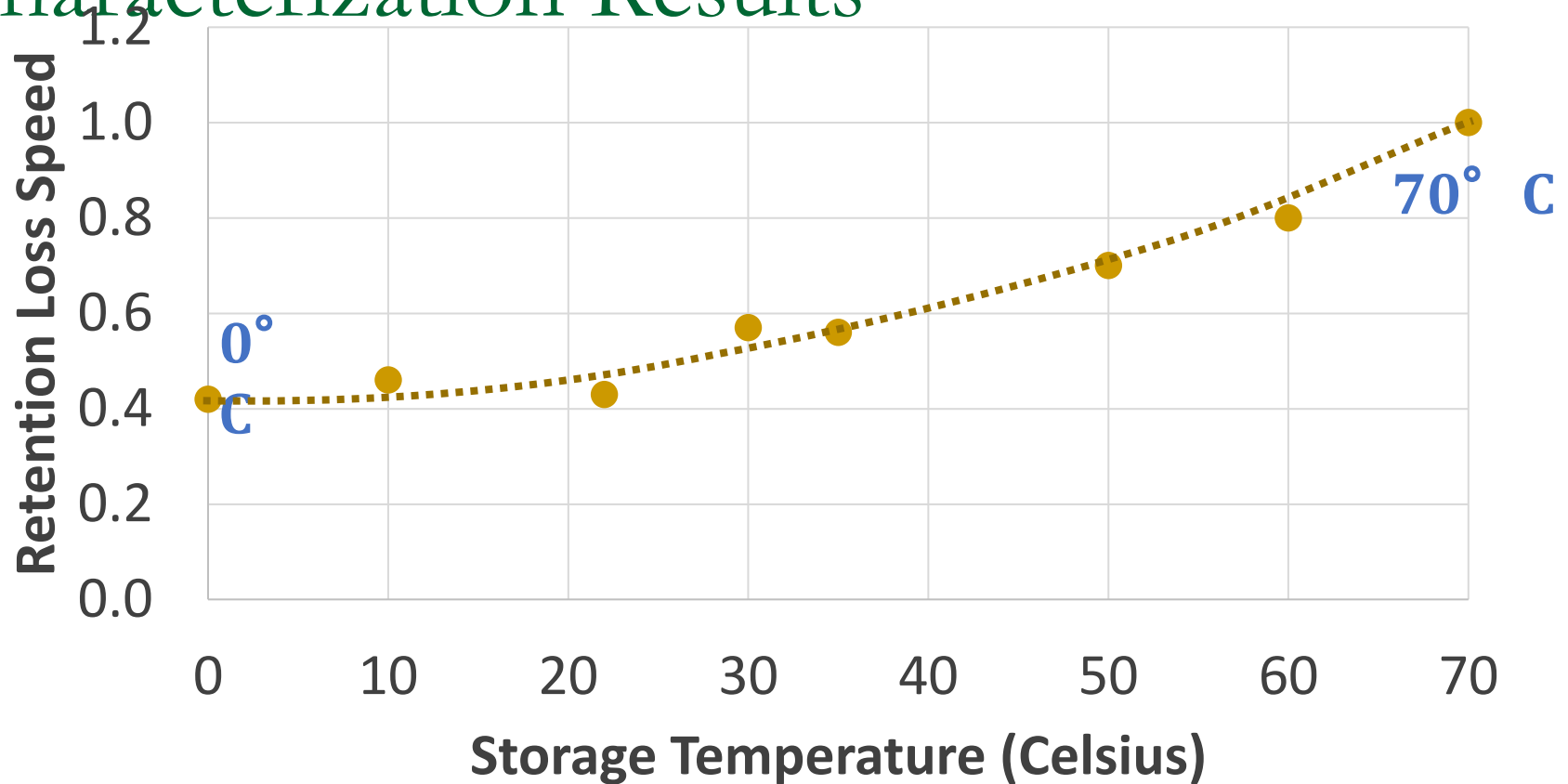
## Characterization Results



**Increasing program temperature from 0°C to 70°C improves program variation by 21%**

# Storage Temperature Effect

## Characterization Results



**Lowering storage temperature from 70°C to 0°C slows down retention loss speed by 58%**

# Characterization Summary

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## Major Results:

- *Self-recovery* affects retention loss speed
- Program *temperature* affects program variation
- *Storage temperature* affects retention loss speed

## Unified Model

## Other Characterizations Methods in the Paper:

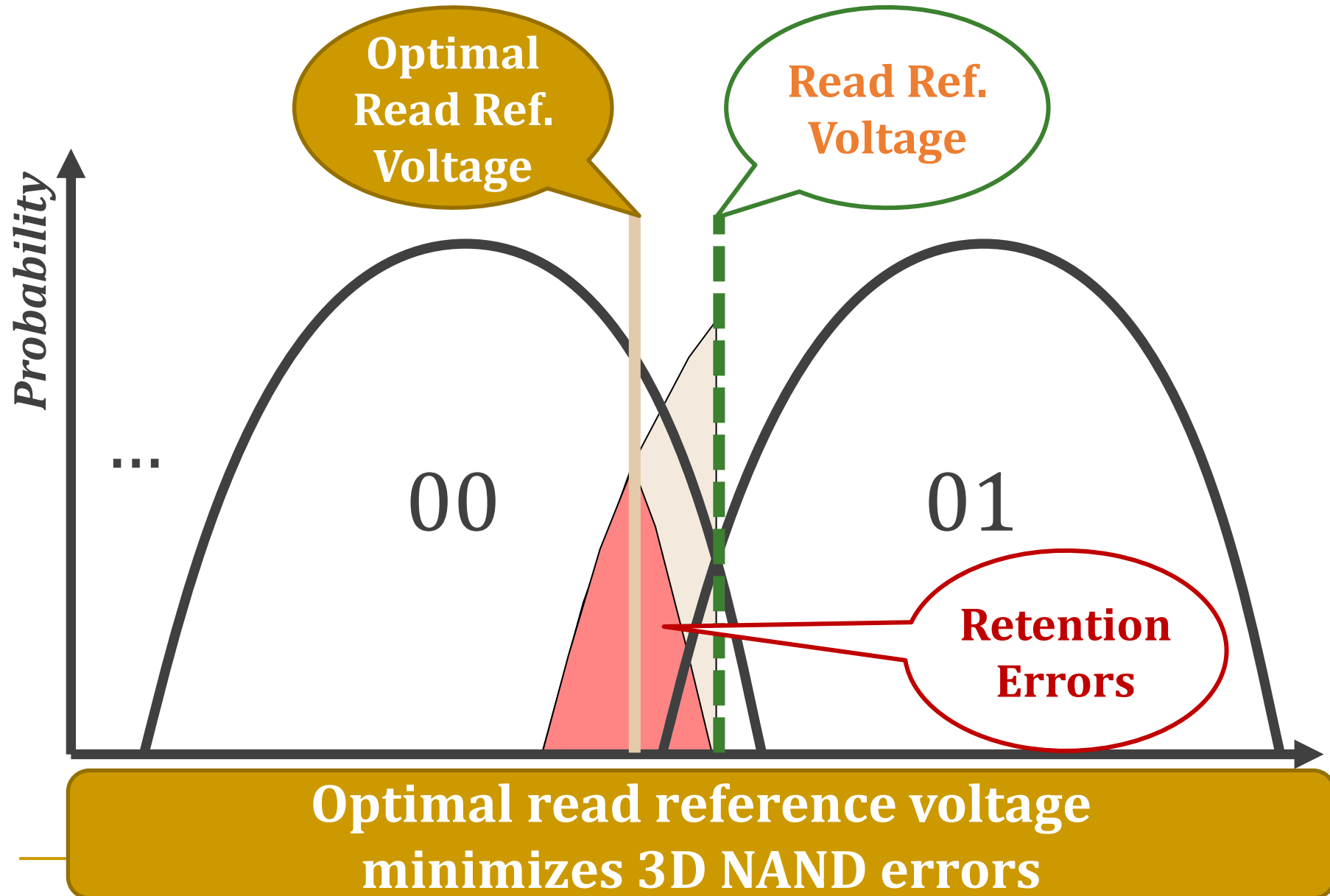
- More detailed results on self-recovery and temperature
  - Effects on error rate
  - Effects on threshold voltage distribution
- Effects of recovery cycle (P/E cycles with

# Outline

---

- Executive Summary
- Background on NAND Flash Reliability
- Characterization of Self-Recovery and Temperature Effect on Real 3D NAND Flash Memory Chips
- **URT: Unified Self-Recovery and Temperature Model**
- HeatWatch Mechanism
- Conclusion

# Minimizing 3D NAND Errors



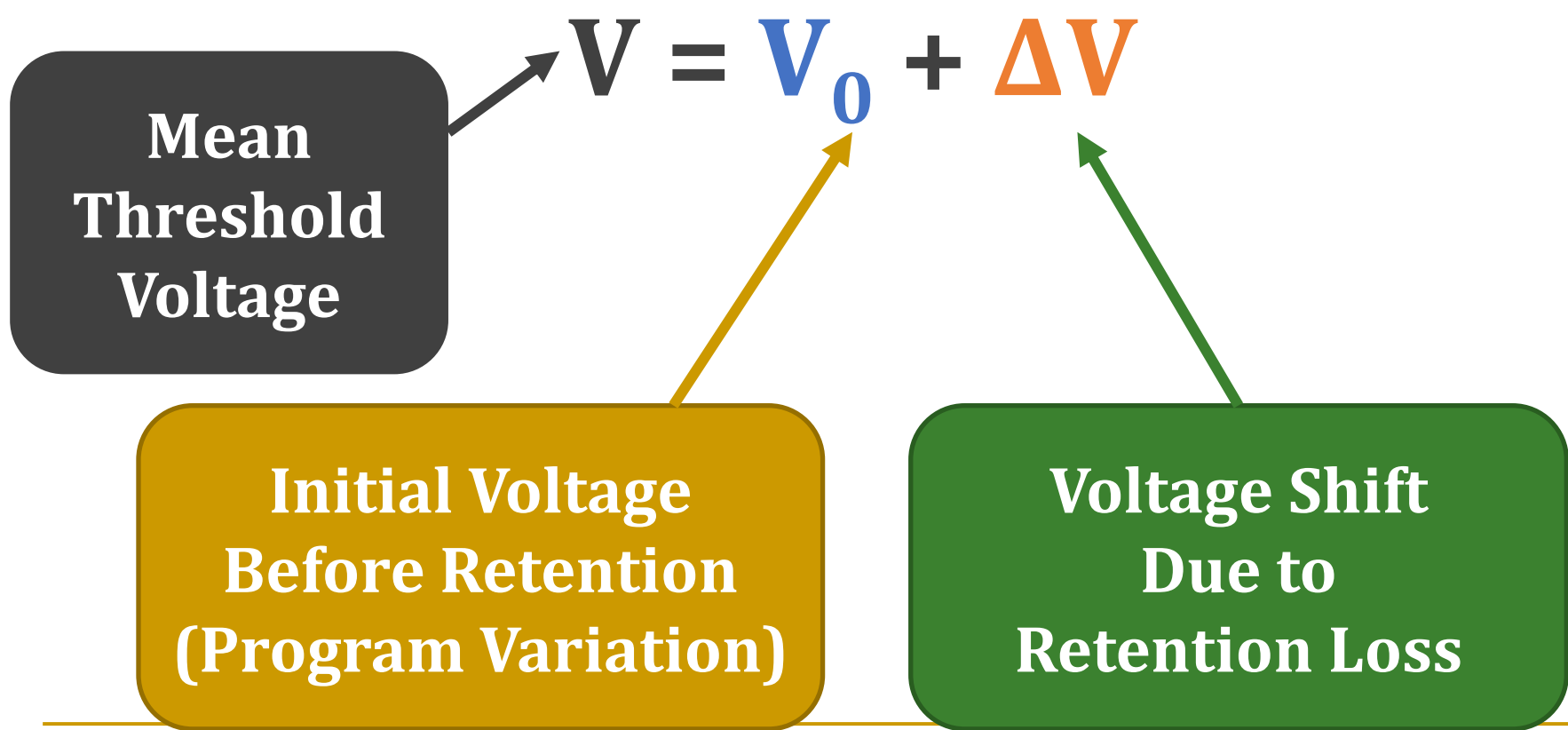
# Predicting the Mean Threshold Voltage

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## Our URT Model:

$$V = V_0 + \Delta V$$

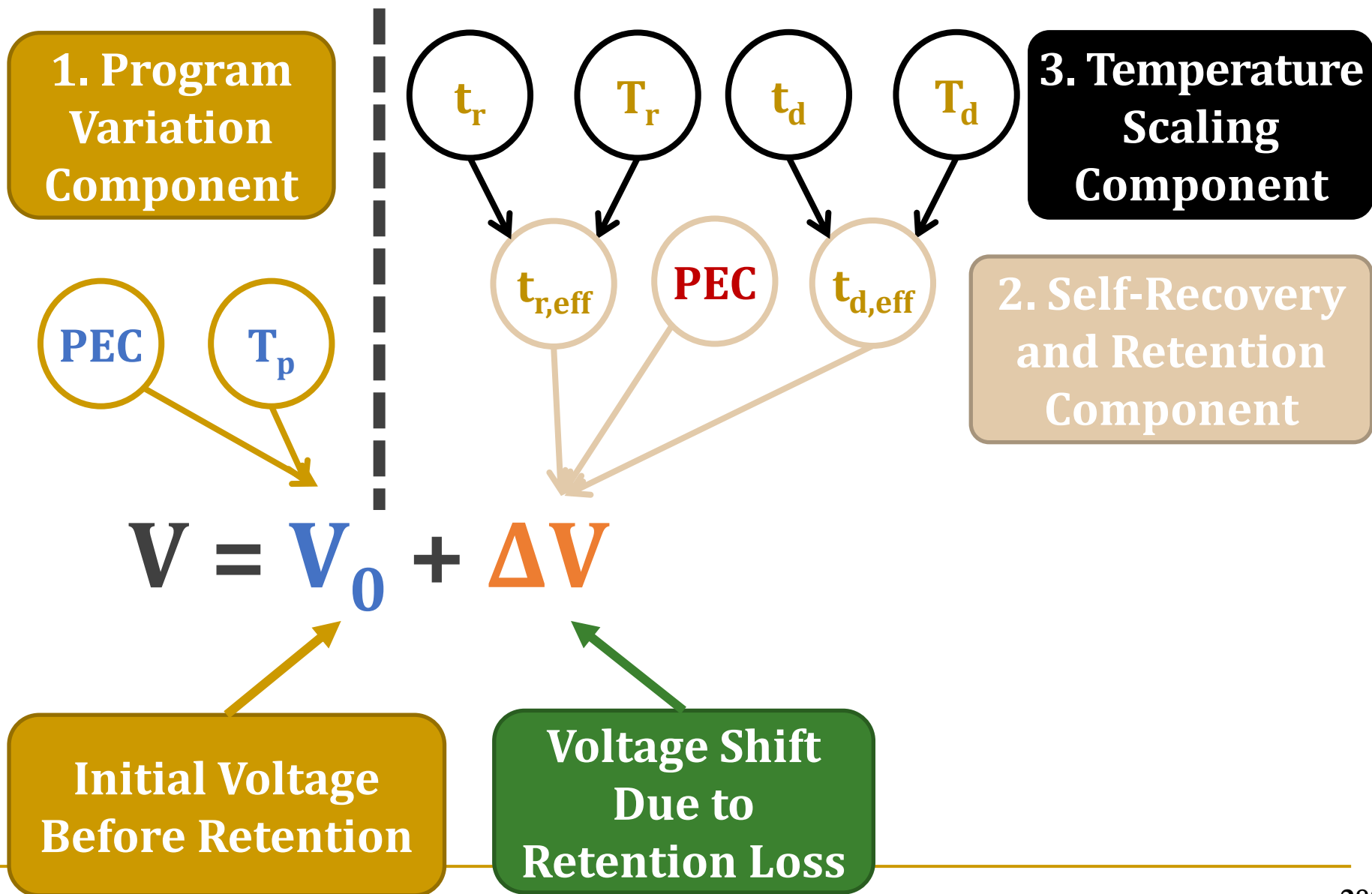
Mean  
Threshold  
Voltage



Initial Voltage  
Before Retention  
(Program Variation)

Voltage Shift  
Due to  
Retention Loss

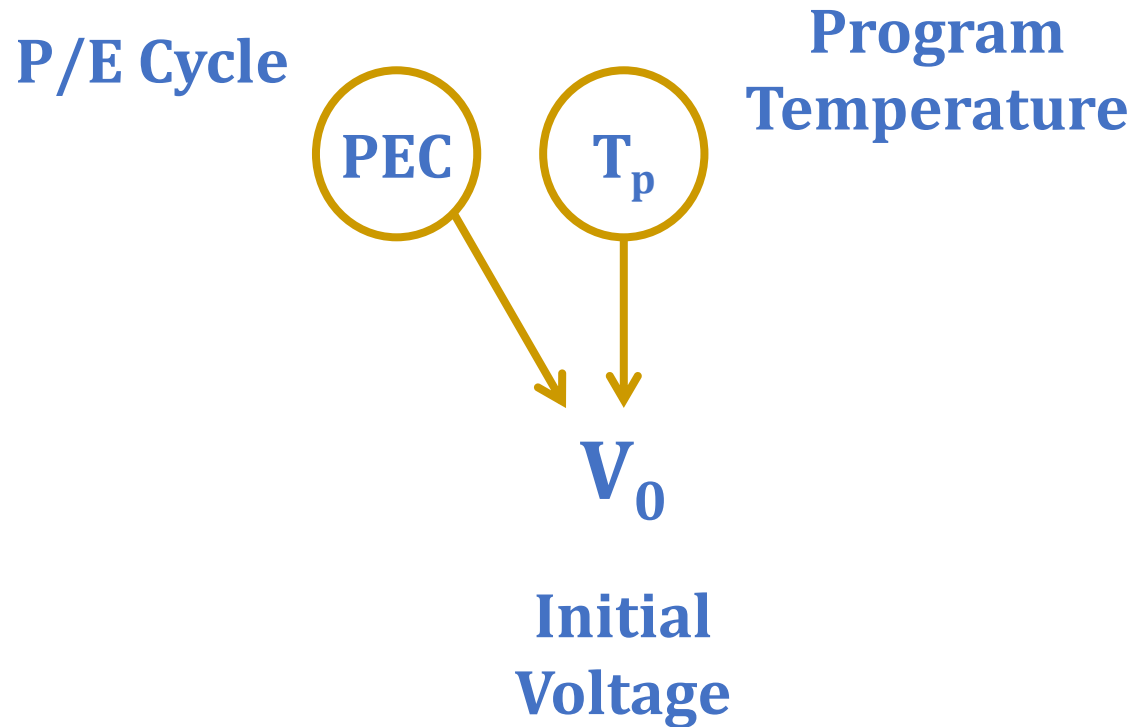
# URT Model Overview





# 1. Program Variation Component

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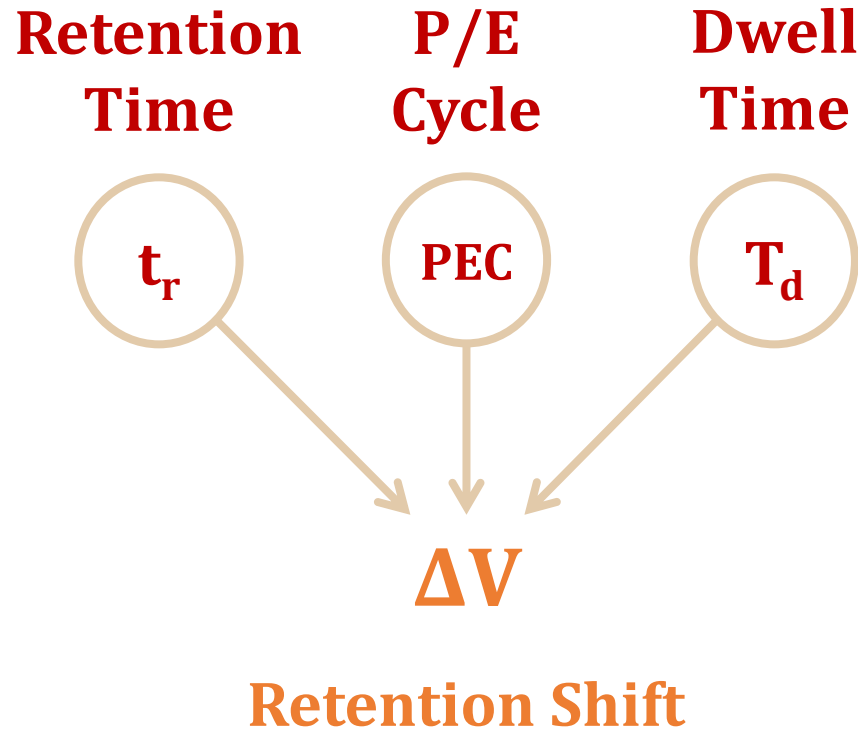
$$V_0 = A \cdot T_p \cdot PEC + B \cdot T_p + C \cdot PEC + D$$



Validation:  $R^2 = 91.7\%$

## 2. Self-Recovery and Retention Component

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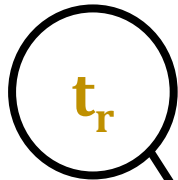


$$\Delta V(t_{er}, t_{ed}, PEC) = b \cdot (PEC + c) \cdot \ln \left( 1 + \frac{t_{er}}{t_0 + a \cdot t_{ed}} \right)$$

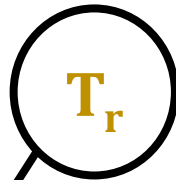
✓ Validation: 3x more accurate  
than state-of-the-art model

### 3. Temperature Scaling Component

**Actual  
Retention  
Time**

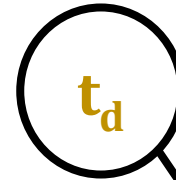


**Storage  
Temp.**

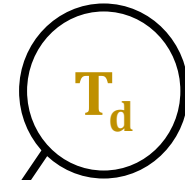


**Effective  
Retention Time**

**Actual  
Dwell  
Time**



**Dwell  
Temp.**



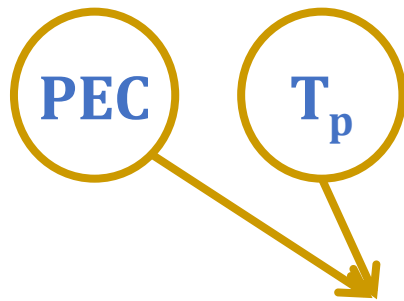
**Effective Dwell  
Time**

*Arrhenius Equation:*  $AF = \frac{t_{real}}{t_{room}} = \exp \left( \frac{E_a}{k_B} \cdot \left( \frac{1}{T_{real}} - \frac{1}{T_{room}} \right) \right)$

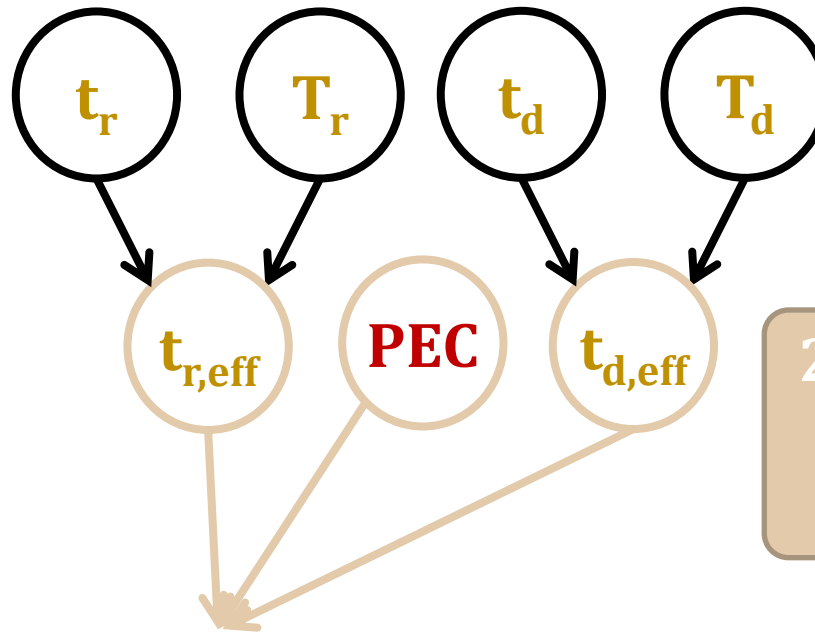
✓ **Validation: Adjust an important parameter,  
 $E_a$ , from 1.1 eV to 1.04 eV**

# URT Model Summary

1. Program Variation Component



$$V = V_0 + \Delta V$$



3. Temperature Scaling Component

2. Self-Recovery and Retention Component

Validation:

Prediction Error Rate = 4.9%

# Outline

---

- Executive Summary
- Background on NAND Flash Reliability
- Characterization of Self-Recovery and Temperature Effect on Real 3D NAND Flash Memory Chips
- URT: Unified Self-Recovery and Temperature Model
- **HeatWatch Mechanism**
- Conclusion

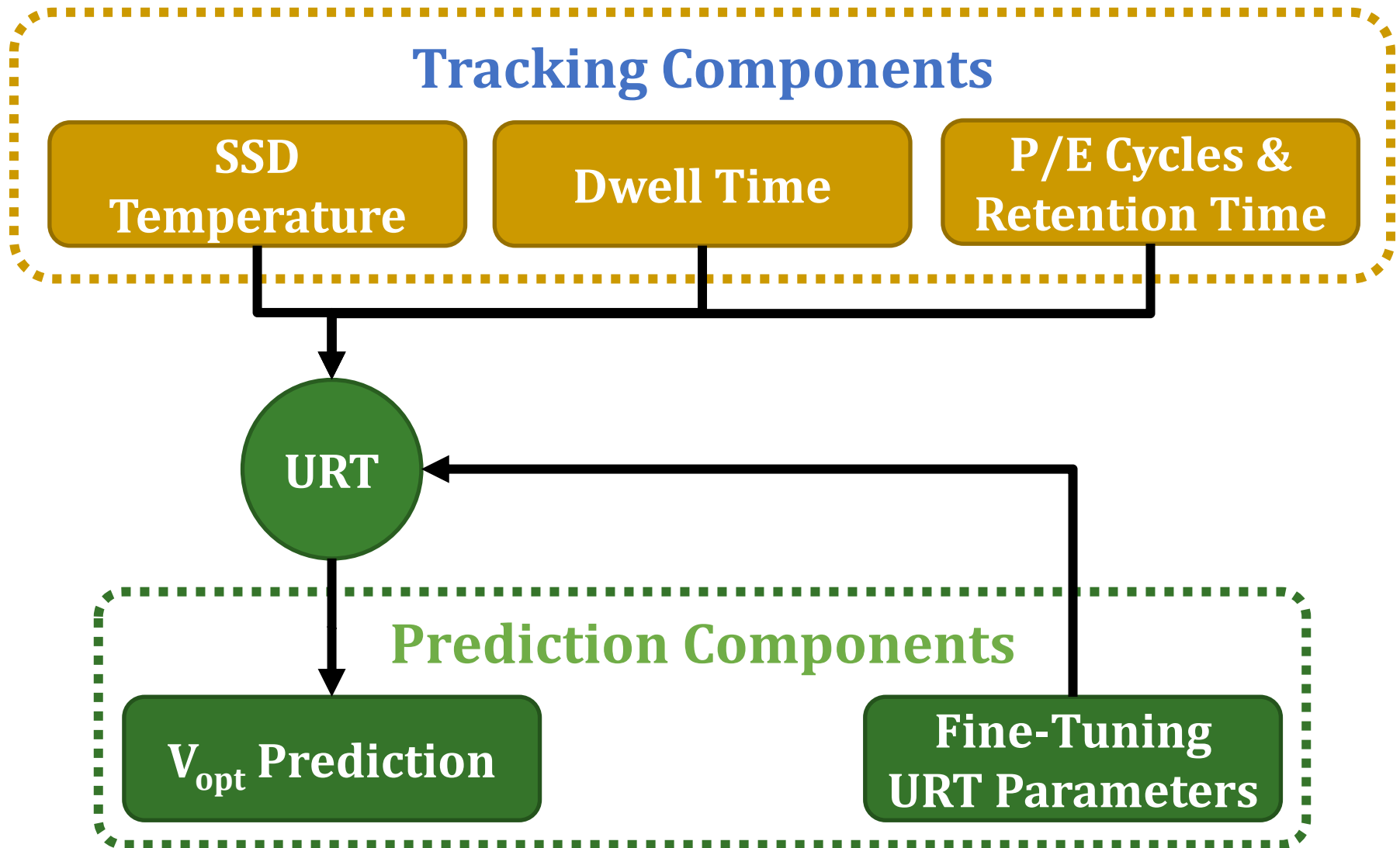
# HeatWatch Mechanism

---

## ■ Key Idea

- Predict change in threshold voltage distribution by using the URT model
- Adapt read reference voltage to near-optimal ( $V_{\text{opt}}$ ) based on predicted change in voltage distribution

# HeatWatch Mechanism Overview



# Tracking SSD Temperature

## Tracking Components

SSD  
Temperature

Dwell Time

P/E Cycles &  
Retention Time

- Use existing sensors in the SSD
- **Precompute** temperature scaling factor at **logarithmic time intervals**

## Prediction Components

$V_{\text{opt}}$  Prediction

Fine-Tuning  
URT Parameters



# Tracking Dwell Time

## Tracking Components

SSD  
Temperature

Dwell Time

P/E Cycles &  
Retention Time

- Only need to log the timestamps of **last 20 full drive writes**
- Self-recovery effect diminishes after 20 P/E cycles

## Prediction Components

$V_{\text{opt}}$  Prediction

Fine-Tuning  
URT Parameters

# Tracking P/E Cycles and Retention Time

## Tracking Components

SSD  
Temperature

Dwell Time

P/E Cycles &  
Retention Time

- P/E cycle count **already recorded** by SSD
- **Log write timestamp** for each block
- Retention time = read timestamp – write timestamp

## Prediction Components

$V_{opt}$  Prediction

Fine-Tuning  
URT Parameters

# Predicting Optimal Read Reference

Voltage

## Tracking Components

SSD  
Temperature

Dwell Time

P/E Cycles &  
Retention Time

- **Calculate URT** using tracked information
- Modeling error: 4.9%

## Prediction Components

$V_{\text{opt}}$  Prediction

Fine-Tuning  
URT Parameters

# Fine-Tuning URT Parameters Online

## Tracking Components

SSD  
Temperature

Dwell Time

P/E Cycles &  
Retention Time

- Accommodates **chip-to-chip** variation
- Uses **periodic** sampling

## Prediction Components

$V_{\text{opt}}$  Prediction

Fine-Tuning  
URT Parameters

# HeatWatch Mechanism Summary

## Tracking Components

SSD  
Temperature

Dwell Time

P/E Cycles &  
Retention Time

Storage Overhead: 0.16% of DRAM in 1TB SSD

URT

## Prediction Components

$V_{\text{opt}}$  Prediction

Fine-Tuning  
URT Parameters

Latency Overhead: < 1% of flash read latency

# HeatWatch Evaluation Methodology

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- 28 real workload storage traces

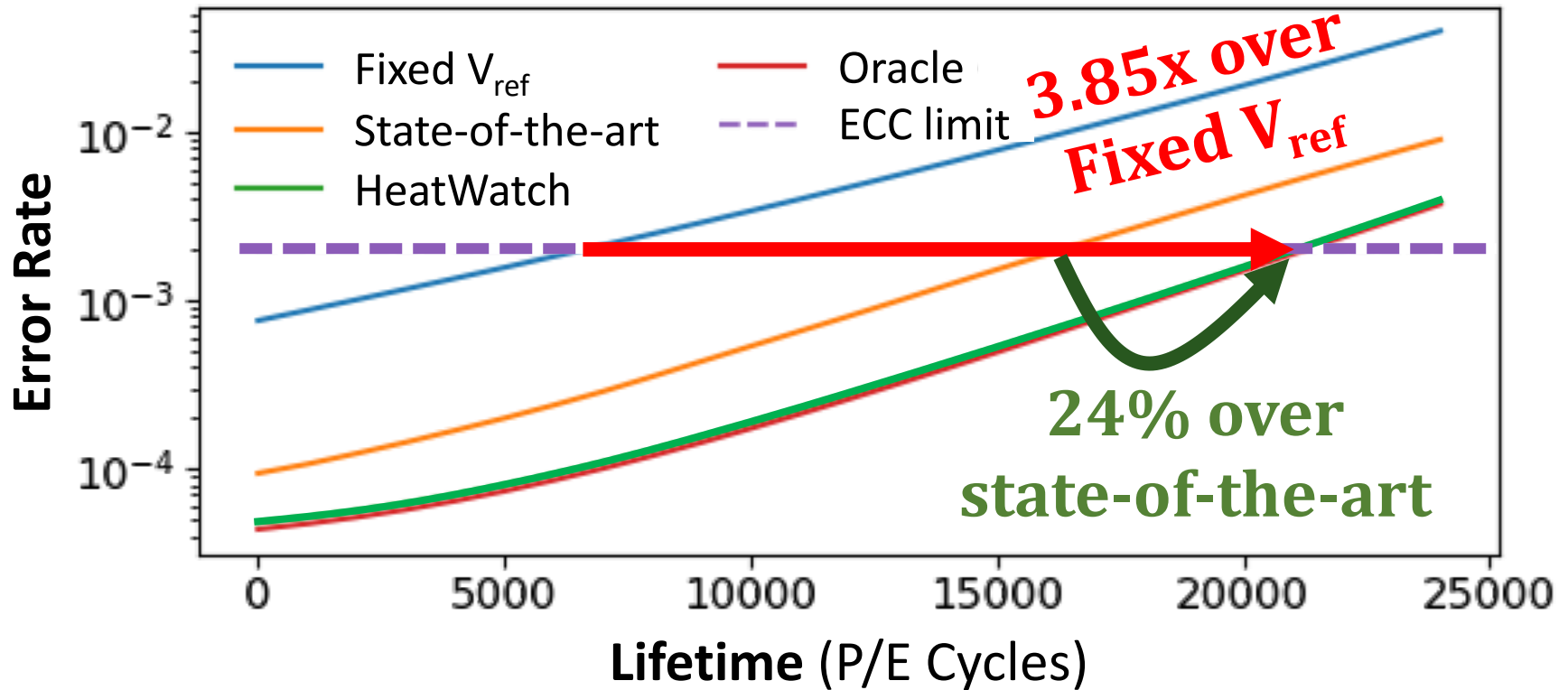
- MSR-Cambridge
- We use **real dwell time, retention time values** obtained from traces

- Temperature Model:

Trigonometric function + Gaussian noise

- Represents periodic temperature variation in each day
- Includes small transient temperature variation

# HeatWatch Greatly Improves Flash Lifetime



HeatWatch improves lifetime by capturing the effect of retention, wearout, self-recovery, temperature

# Outline

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- Executive Summary
- Background on NAND Flash Reliability
- Characterization of Self-Recovery and Temperature Effect on Real 3D NAND Flash Memory Chips
- URT: Unified Self-Recovery and Temperature Model
- HeatWatch Mechanism
- **Conclusion**



# Conclusion

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- 3D NAND flash memory susceptible to **retention errors**
  - ❑ Charge leaks out of flash cell
  - ❑ Two unreported factors: **self-recovery** and

- **Experimental characterization** of *real* 3D NAND chips

- **Unified Self-Recovery and Temperature (URT) Model**

- Predicts impact of retention loss, wearout, self-recovery, temperature on **flash cell voltage**
- **Low prediction error rate: 4.9%**

- **HeatWatch**

- Uses URT model to find optimal read voltages for 3D NAND flash
- **Improves flash lifetime by 3.85x**

# *HeatWatch*

Improving 3D NAND Flash Memory Device Reliability by  
Exploiting Self-Recovery and Temperature Awareness

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